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Energy Conservation Potential of Surface Modification Technologies

September 1985

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PNL-5538

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Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PNL-5538
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ENERGY CONSERVATION POTENTIAL OF SURFACE MODIFICATION TECHNOLOGIES

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September 1985

Prepared for
Energy Conversion and
Utilization Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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EXECUTIVE SUMMARY OF TRIBOLOGY SERIES

Experts estimate that in 1978 over four quadrillion Btu of energy were lost in the United States because of simple friction and wear--enough energy to supply New York City for an entire year. This translates to a $20 billion loss, based on oil prices of about $30 per barrel.[a] Because of the enormity of this energy loss, the Energy Conversion and Utilization Technologies (ECUT) Program in the U.S. Department of Energy (DOE) initiated a program in 1983 to study tribology--the science of friction and wear--to learn more about the causes of these energy losses (or tribological "sinks") and how to reduce them.

The ECUT Program itself was started in 1980 to encourage research to improve energy conversion and utilization efficiency. The enormous energy loss in tribological sinks has been targeted by the ECUT program as having significant potential for energy conservation. One goal of the ECUT Tribology Program is to reduce these energy losses by developing improved lubricants and more durable materials.

To support initial Tribology Program planning, ECUT conducted six surveys to gather three types of information about the current tribology problem in the U.S.:

1. The identification of typical industrial sinks
2. A survey of current U.S. Government tribology projects
3. The identification of tribology R&D needs based on industry perceptions.

The six ECUT-sponsored surveys are listed in Table ES.1. Each survey is being published as a separate volume with its own summary. This executive summary, which also appears in each of the six volumes, presents an overview of results from the six surveys and their implications for energy conservation. The results of these six surveys and their implications for energy conservation are presented in this summary. These results will be used to support further research planning for the ECUT Tribology Program.

TABLE ES.1. ECUT Surveys Reviewed in this Summary

1. A Review of Tribological Sinks in Six Major Industries. Imhoff, et al. PNL-5535, Pacific Northwest Laboratory, Richland, Washington.
2. Reduction in Tribological Energy Losses in the Transportation and Electric Utilities Sectors. Pinkus and Wilcock, Mechanical Technology Incorporated. PNL-5536, Pacific Northwest Laboratory, Richland, Washington.
3. Identification of Tribological Research and Development Needs for Lubrication of Advanced Heat Engines. Fehrenbacher, Technology Assessment and Transfer, Incorporated. PNL-5537, Pacific Northwest Laboratory, Richland, Washington.
4. Energy Conservation Potential of Surface Modification Technologies. Le, DHR, Inc. PNL-5538, Pacific Northwest Laboratory, Richland, Washington.
5. Assessment of Government Tribology Programs. Peterson, Wear Sciences Corporation. PNL-5539, Pacific Northwest Laboratory, Richland, Washington.
6. Assessment of Industrial Attitudes Toward Generic Research Needs in Tribology. Sibley and Zlotnick, Tribology Consultants Incorporated. PNL-5540, Pacific Northwest Laboratory, Richland, Washington.

IDENTIFYING TYPICAL TRIBOLOGICAL SINKS AND MECHANISMS

ECUT's first step in collecting information about tribology was to identify significant tribological sinks and mechanisms. This information was needed to focus research on key technological problems. Because the industry, transportation, and utilities sectors account for most of the

(a) Calculations in this summary are based on a $30 figure.

energy consumed in the U.S., ECUT concentrated first on the tribological energy sinks and mechanisms found in these three sectors. The report by Imhoff, et al., describes the most important tribological sinks typically found in industry, and the report by Pinkus and Wilcock describes tribological energy losses in the transportation and utilities sectors. Two specific studies assessed tribological problems in the metalworking industry and in the advanced diesel engine.

To identify areas in which tribology has a significant impact, the authors examined the energy consumed, the fuels used, and the primary products and processes found in the transportation, industrial, and utilities sectors. Once energy losses were identified, their magnitude was estimated. The estimates include both friction losses (direct losses) and material wear losses (indirect losses). The authors also estimated the energy savings potential in each sector and recommended some specific R&D programs to help achieve these energy savings.

The Industrial Sector

Tribological energy losses are pervasive throughout industry. Because reviewing all industries and industrial processes in detail would be impossible, the Imhoff, et al. survey, instead chose six representative industries (Mining, Agriculture, Primary Metals, Chemicals/Refining, Pulp and Paper, and Food Processing) that appeared to have the most significant tribological sinks and energy losses. These industries were selected because of their 1) major, nonthermal energy streams (such as machine drives); 2) high material wear rates and friction; 3) significant material transportation/alteration processes; and 4) total energy use.

The study identified important tribological sinks in each selected industry, based on both friction and material wear energy losses and on the tribological mechanisms and materials involved. Figure ES.1 and Table ES.2 show the key results for each of the six industries.

The first conclusion from this study confirmed earlier claims that losses from material wear are greater than energy losses from friction; the wear losses in five of the industries were found to be more than twice as large as the friction losses.[a] The study also concluded that reducing material wear rates to improve equipment life

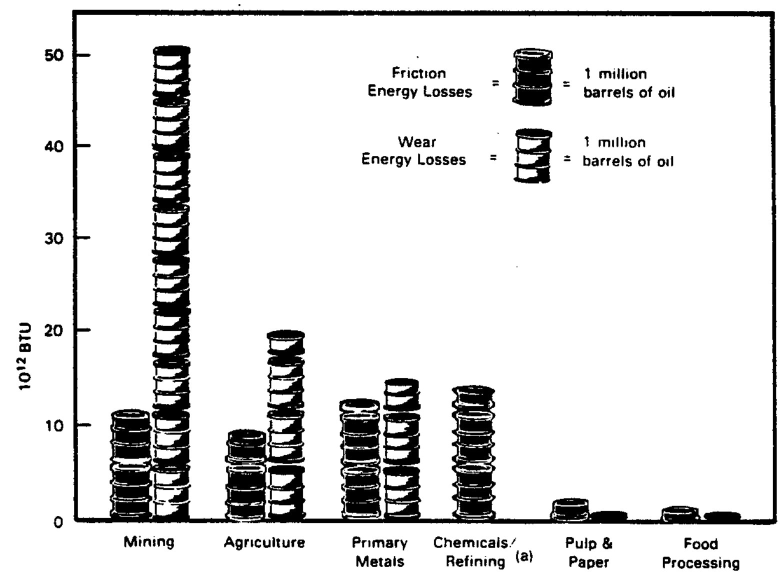

FIGURE ES.1. Annual Friction and Wear Losses in Surveyed Industries

(a) These five industries had estimates of both friction and material wear losses; the sixth, Chemicals/Refining, did not have estimates of wear losses.

TABLE ES.2. Primary Mechanisms in Friction Energy Losses and Principal Materials Involved in Wear Energy Losses

Industry	Mechanisms	Materials
Mining	3-body Abrasion Friction	Iron, Steel & alloys, Aluminum, Rubber
Agriculture	3-body Abrasion Friction	Steel, Rubber, Lubricants
Primary Metals	Hot Rolling Inefficiencies	Steel & alloys
Chemicals/Refining	Friction, Erosion Abrasion	Not studied
Pulp & Paper	Friction	Steel & alloys, Chromium-Molybdenum alloys Grinding stones
Food Processing	Erosion, Abrasion	Steel & alloys

and reliability would also significantly improve industrial productivity. The industry representatives interviewed strongly emphasized the positive impacts that tribological research could have on operational productivity.

Tribology in the Metalworking Industry

In addition to the general review of tribological sinks in industry, ECUT sponsored a more specific study of tribology in the metalworking industry by Le Khac at DHR, Inc. The study estimated the energy conservation potential of using advanced surface modification technologies in this industry. These surface modification technologies are thermal, chemical, or mechanical treatments that reduce friction and wear at a material's surface without changing its bulk properties. The advanced surface modification technologies considered were ion implantation, laser surface hardening, electron beam surface hardening, and wear-resistant coating deposition. The author studied 70 percent of the metal-forming and metal-cutting machines used in the United States (except those associated with primary metals processing), identified tribological mechanisms, and estimated friction and wear energy losses. Potential energy savings from using surface-modified tools were also estimated.

The metal-forming machines studied were punches, presses and forges, and the metal-cutting machines studied were turning, drilling, milling, broaching, and sawing machines. Models were developed to estimate friction and wear energy losses and potential savings. The friction losses were estimated by adding friction losses at the motor drive system and at the tool-workpiece interface. Estimates of energy consumption were based on standard operating conditions (known friction coefficients, total working time, etc.) The indirect losses from wear were estimated based on the replacement costs of all metalworking tools used and discarded in one year.

Based on actual experimental or production data, the author estimated that the friction losses in all U.S. metalworking machines amount to 20.2×10^{12} Btu per year, or \$104.5 million. Of this energy loss, 1.8×10^{12} Btu per year, or 9%, could be saved using surface modification technologies to reduce friction. The wear loss was estimated to be 7.7×10^{12} Btu per year.[a] Possible energy savings using surface modification technologies to reduce wear could conserve 5.5×10^{12} Btu per year, or 71%.

Finally, the author estimated that tribological energy losses in all U.S. metalworking machines total 27.9×10^{12} Btu, equivalent to 4.8 million barrels of oil or \$144 million annually. More than a quarter of this loss could be saved using surface modification technologies to reduce friction and wear. These results are shown in Figure ES.2.

(a) Using 19.2 million Btu per ton as the embodied energy in steels.

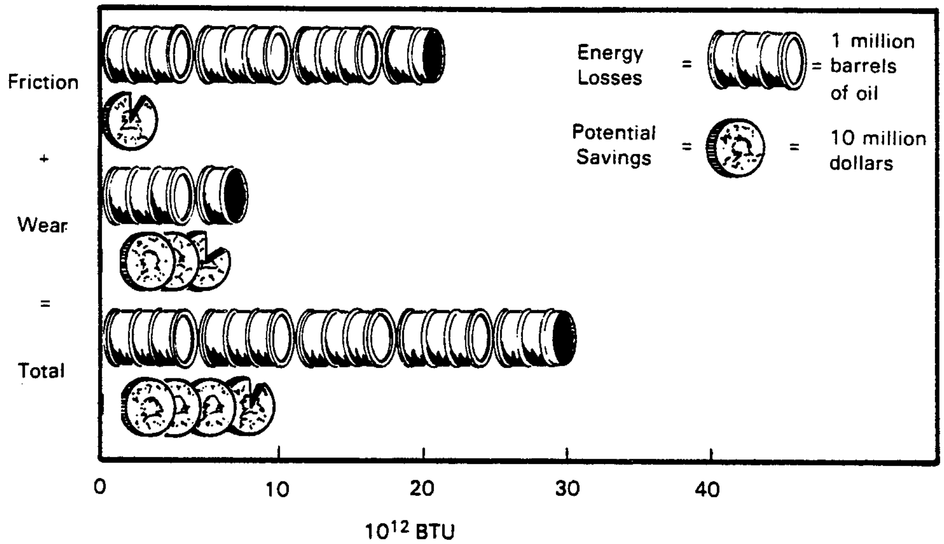

FIGURE ES.2. Annual Friction and Wear Energy Losses in the Metalworking Industry, and Potential Savings from Surface Modification Technologies

The Transportation Sector

The transportation sector is important both in terms of its energy consumption (26% of total U.S. annual energy consumption, or 19×10^{15} Btu, equivalent to \$98 billion), and because of the high level of tribological losses. The Pinkus and Wilcock study primarily focused on the highway fleets (passenger cars, buses and trucks), which consume 77% of the total energy used in the transportation sector. The survey primarily addressed the conventional Otto cycle engine. However, other concepts were also considered, such as the adiabatic diesel, the gas turbine, and the Stirling engine; in addition, the Fehrenbacher report evaluated tribological activity in advanced diesel engines.

Figure ES.3 shows the principal automotive tribological sinks and the estimated energy savings. The principal automotive energy sinks are caused by the mechanical inefficiency of the engines and drive trains; most of the energy losses are due to friction.

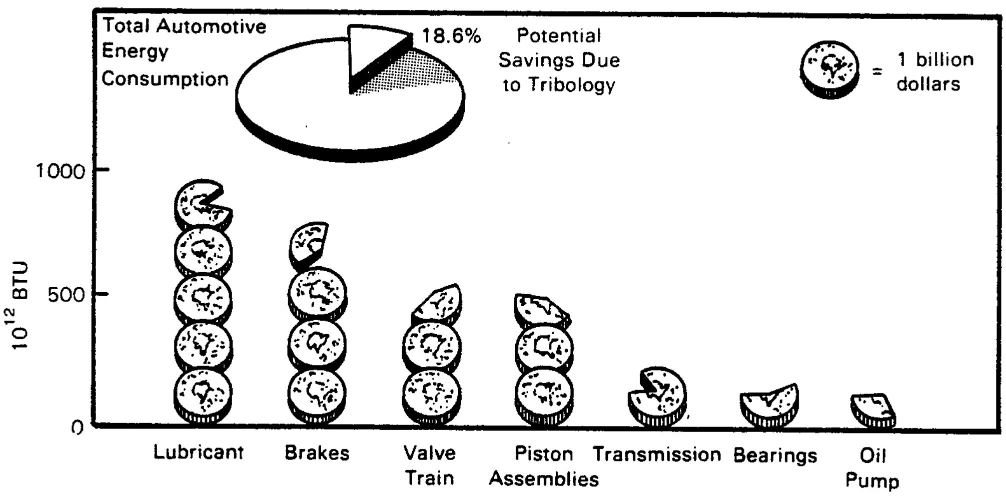

FIGURE ES.3. Potential Energy Savings Per Year for the Conventional Engine (Based on highway fleet size in 1976)

The survey by Pinkus and Wilcock revealed several tribological areas of particular concern for conventional engines, such as the piston ring assembly and the long-range effect of low-viscosity oil on engine wear. As shown in Figure ES.3, tribological improvements could save 18.6% of the total annual energy consumed by automobiles, or $14.3 billion.

Research on conventional engines often applies to unconventional engines as well. Except for the adiabatic diesel, the energy savings possible from tribological improvements to unconventional engines are less significant than those of the conventional Otto cycle engine. The major problems in unconventional engines are related to high-temperature tribological problems. Introducing adiabatic and minimum friction engines into the bus and truck fleets of the U.S. could save up to 2.9% of total U.S. energy consumption.

This survey also revealed the difficulties with devising adequate performance tests to quantify energy losses and evaluate new designs and products. Laboratory tests that accurately reflect real-world conditions are badly needed. The ability to test entire systems is vital, since tribological energy losses are often caused by complex interactions between all the components of a system.

Advanced Diesel Engines

Because of the great potential for energy savings, the ECUT study by Fehrenbacher examined the lubrication of advanced diesel engines in detail. The efficiency of these engines could be improved by about 10%; however, higher operating temperatures (1000°F and higher in the upper cylinder area) are required to reach this greater efficiency. As a result, the primary development challenge for these engines concerns friction, wear, and lubrication of the upper cylinder region. In fact, tribological advancements in these areas are essential if diesel engine performance and durability goals are to be reached. This study assessed these vital tribological concerns in both current and future technologies and recommended tribology R&D topics for further advanced engine development.

Both the mechanical design of the upper cylinder and the chemical effects of lubricants and fuel determine the friction and wear characteristics of the upper cylinder region. These two factors interact in a complex and sometimes synergistic manner. The geometry of the piston, piston ring, and cylinder directly affect the rate and nature of deposit formation, oil consumption, and friction. Efforts have been made to optimize the upper cylinder geometry in current diesel engine technology; this will also be a critical area in future developments. However, problems with upper cylinder deposits, bore polishing, and oil consumption still exist. This study indicates that these problems are caused by the chemical interactions between upper cylinder materials, oil degradation products, and fuel combustion by-products. Therefore, lubricants, oil degradation rates, and mechanisms will continue to be important research areas.

Although a great deal of research has been conducted on liquid lubricants, in most cases the lubricants have been tested without considering the tribological factors specific to the upper cylinder. Since the lubricants interact with the materials and environment of the upper cylinder, they must be developed and tested under similar conditions.

The ECUT study also pointed out that future advanced engine concepts will require ceramic upper cylinder materials able to withstand the higher operating temperatures. New lubricants will have to be developed, and solid lubricants are likely to play a major role. A major research effort will be needed in this area; again, the research must be conducted on a total system basis to be most effective.

The study concluded that many problems with current diesel engines will continue to exist in advanced diesel engines. Tribological problems in the upper cylinder region will be most critical in terms of engine performance and wear. Lubricant R&D is still a major research area in current technology, but total system materials and design considerations should be emphasized. Advanced diesel concepts will require new design approaches, but the tribology of the upper cylinder region will still be critical and may even be the limiting factor in achieving higher engine efficiencies. Extensive materials R&D will be required for advanced designs as well, especially in ceramics, ceramic composites and solid lubricants.

The Utilities Sector

The utilities sector was also reviewed for significant tribology sinks. This sector accounts for roughly 28% of total U.S. energy consumption. ECUT's review revealed that tribological improvements in efficiency and reliability could save 2.3% of the total energy annually consumed by utilities, or about $2.5 billion. As in the transportation sector, efficiency is a major factor.

However, reliability (especially in generating units) is just as important for energy conservation.

The data used in these studies were primarily for the utilities' power plants. The average power plant operates at an efficiency (output energy/input energy) between 30 and 40%. Mechanical losses account for 17-26% of the total energy used. Reliability problems that lead to generator shutdown require using standby equipment, which generally has less efficient fuel consumption. This causes losses both in terms of fuel economy, and revenue and labor costs. Tribological problems are estimated to cause as much as 5% of the reliability problems that require shutdown. Furthermore, tribology-caused shutdowns increase with the size of the power generating unit.

The ECUT survey found several tribological areas with significant energy savings potential, including gas path leakage, seals, and bearings on both the main turbine generator and on the various accessories. Different forms of bearing and lubricant problems (contaminated oils, pump problems, etc.) and vibrations are the leading causes of the plant shutdowns.

Figure ES.4 summarizes potential savings from improving tribological problems in the electric utilities. For accessories, the major concern is sealing problems with feedwater pumps. Friction and wear are implicated in much of the seal and bearing losses. The major problems identified in this study will require research on lubrication theory and advanced materials and coatings developments.

CURRENT U.S. GOVERNMENT PROGRAMS

The second part of ECUT's information collecting efforts involved identifying tribology R&D currently being sponsored or conducted by the U.S. Government. This information was needed to avoid duplicating existing research and to locate those areas that need more research support. The Peterson study identified 215 current projects sponsored by 21 different government organizations. The study classified these projects by subject, objective, energy conservation relevance, type of research, phenomena and variables being investigated, materials, and applications. The principal government sponsors include the Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), National Bureau of Standards (NBS), and DOE.

The study located these tribology projects initially by using information from literature searches. Data bases used included the Smithsonian Science Information Exchange, the Defense Technical Information Center's Research and Technology Work Unit Information System, and the Materials Science Abstracts of the National Technical Information Service (NTIS). The study located a

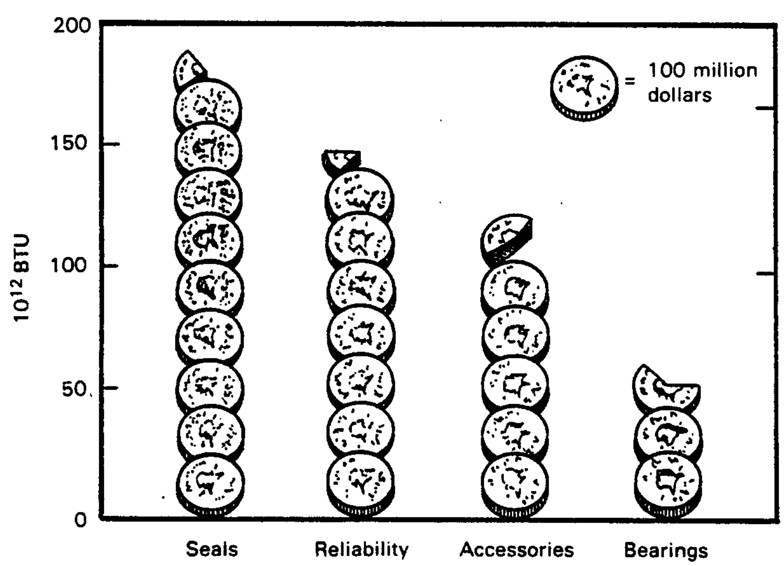

FIGURE ES.4. Potential Energy Savings for the Utilities (Based on estimates of installed capacity in 1983 and on an energy cost of $30 per barrel.)

total of 640 government-sponsored projects covering the fiscal years 1978-1983. These organizations were then contacted by mail, followed by visits and/or phone discussion. Of the original 640 projects, 215 were found to be current. A detailed description of each project is included in the report.

According to this study, until several years ago tribology research emphasized component development, fluid film and elastohydrodynamic lubrication, and concentrated contacts. Since then the emphasis has shifted dramatically, and research efforts now concentrate on lubricants, materials and coatings, and friction and wear mechanisms. There is still considerable interest in rolling contact bearings and seals, as well as in early failure detection in maintenance technology.

The study also concluded that most current tribology research is related to DOD objectives of longer life, low maintenance/failure-free machinery, and the basic understanding of friction, wear, materials, and coatings. High-temperature lubrication also continues to be a major objective in tribology research; the effects of new materials and solid lubricants on current temperature limitations are also being studied. Coatings are receiving the most attention in general materials development. Figure ES.5 shows a breakdown of the materials considered in the 215 projects.

The author also concluded that current programs generally do not emphasize energy or materials conservation. Design predictability and composite materials are other areas that are receiving little attention. Finally, the study concluded that current U.S. Government high-temperature lubrication work is the most applicable to energy conservation goals.

INDUSTRY PERCEPTIONS OF GENERIC RESEARCH NEEDS IN TRIBOLOGY

Because transferring information to industries is a major part of the ECUT program, ECUT conducted a survey of industry perspectives on tribology R&D needs. This survey, conducted by Sibley and Zlotnick, involved interviewing industry contacts to discover what research results are needed.

The authors held in-depth discussions with engineers and managers from 27 companies. These companies were chosen by defining different tribological categories (such as transportation, power plants, seals, gears, aerospace, etc.). At least one company was then selected for each category, and two or three were chosen for categories that are particularly important to the ECUT program. The purpose of this study was not to produce statistically significant findings, but rather to represent many different viewpoints and a variety of interests.

The authors' main emphasis was on determining the engineering limitations imposed by tribology considerations. They also tried to determine the type and funding level of current generic tribology R&D in each company, although only non-proprietary information was available.[a]

Based on the levels of generic tribology R&D in the 27 individual companies, the authors then estimated total tribology R&D in each industrial segment. Although this approach is obviously limited, reasonably

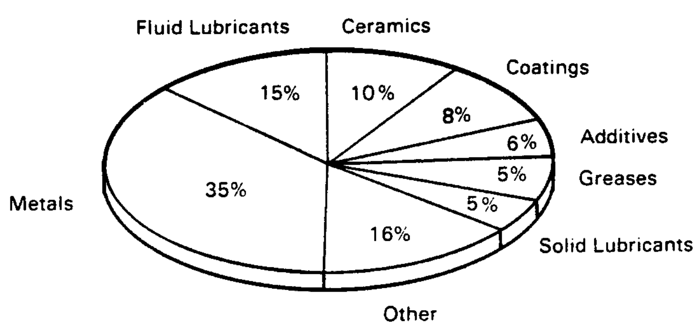

FIGURE ES.5. Materials Under Consideration in the 215 Current Government-Sponsored Tribology Projects

(a) "Generic" R&D in this case is basic research that is not directed toward a specific end use or product.

TABLE ES.3. Estimate of Generic Tribology R&D and Total R&D Budget for Representative Industries (In $M)

Classification	Company	Total R&D[a]	Generic Tribology R&D[b]
Liquid Lubricants	Mobil	188	1
Transportation	Ford	1764	1
Aerospace	Pratt & Whitney	835	0
Powerplants	Caterpillar	234	0
Seals	Crane	10	<1
Rolling Elements	TRW	109	>0
Gears	Eaton	100	>0
Sliding Bearings	Tribon	0	>0
Filters	Pall	7	0
Small Mechanical	Xerox	565	>0
Ceramics	Norton	26	<1
Coatings	Union Carbide	240	<1
Forming	Bethlehem	46	≤1
		4124	6

(a) From the report to the Securities and Exchange Commission for 1982. (Source: "Business Week," June 20, 1983.)
(b) Based on discussions with research staff and referring to only company-funded generic tribology R&D.

accurate estimates were developed of the amounts of generic tribology R&D being conducted in each of the industrial segments. The results for the individual companies are summarized in Table ES.3.

These authors concluded that industry funds only a very limited amount of generic tribology research. Some 'hidden' generic R&D is incorporated into the companies' design manuals, but much of this information is proprietary. As illustrated in Table ES.3, some industry segments have little or no generic tribology R&D. Tribology research efforts are often too small to be likely to improve the state-of-the-art; ceramics is an example of an area in which the funding levels are too small to promote significant advances, although industry has expressed considerable interest in this area. However, the liquid lubricant research budget in the transportation industries is substantial.

The industry representatives expressed interest in the ECUT Tribology Program, and also in obtaining a fundamental physical understanding of tribological mechanisms. The industry contacts also requested more effective presentations of research results, especially results in a form that design and development engineers could readily use. Another industry concern involved developing more realistic laboratory tests and more rational performance standards.

CONCLUSIONS

The six ECUT surveys summarized here were conducted to provide an overview of the major tribological sinks and the current state of U.S. tribology research. Although much of this preliminary ECUT work involved general surveys and samplings, the overall picture is consistent and reveals areas of major concern. The findings in the general surveys have been largely substantiated by the two focused studies on metalworking industries and the advanced diesel engine. These results are being used to support ECUT Tribology Program planning.

These surveys describe the current status of U.S. tribology R&D in 1984; the findings will be updated as necessary. Much of the information is necessarily somewhat speculative and theoretical, and many of the general findings have not yet been fully corroborated. This is due in part to the lack of previous research; improving this initial information should be an important goal of current research. In particular, identifying tribological mechanisms should

be emphasized in order to define specific research projects. Further discussion with industry representatives is also needed.

The five key results from these ECUT studies are listed below:

1. Advanced tribo-materials, coatings, and lubricants must be developed to further improve energy efficiency. Although tribological improvements can be made with the current technology, new and innovative materials and designs (such as the advanced diesel engine) are needed to significantly increase energy efficiency.

2. Tribological mechanisms that shorten equipment life and cause excessive downtime and repair should be identified and studied. Initial research shows that these indirect energy losses from material wear are often greater than the direct energy losses from friction. In addition to the energy conservation impacts, reducing these losses could also significantly improve industrial productivity.

3. Generic tribological research will affect all three major sectors, since similar tribological mechanisms are found in many different processes. Although the transportation sector has the largest tribological energy loss and the greatest potential for energy savings, there is significant energy savings potential in all sectors. Thus research results must be effectively transferred to all sectors.

4. Meaningful performance tests and standards must be developed so that new designs and products can be accurately evaluated. Laboratory tests that accurately reflect real-world conditions are badly needed. Total system testing is vital, since tribological energy losses are often caused by complex interactions between all the components of a system.

5. Continuing communication with industry is critical to ensure that industry research needs are addressed and that the results are adequately transferred.

These results supported the development of the ECUT Tribology Program plan for 1985. The research program is divided into two parts. The Mechanisms component includes such areas as advanced tribo-materials R&D, identifying and characterizing tribological mechanisms, and developing performance test requirements. Projects in this area include developing new tribological materials, and modeling and experimental efforts to determine physical and chemical interactions and processes in tribological systems. Liquid and solid lubricants, tribological coatings and surface modifications, and ceramic and cermet materials are specific topics to be considered. The Mechanisms area also includes efforts to develop novel characterization and testing procedures and diagnostic tools and equipment to assess the performance of tribological systems.

The second part of the research program, Design, includes such topics as design and reliability modeling of components, systems, and system assemblies. Industry is directly involved in these projects. The Design area will also establish a data center to gather and disseminate information on tribology. These projects concentrate on generic tribology R&D, including energy losses from material wear.

Clearly, tribology research can have a major impact on energy use and conservation in the U.S. Much of the needed research identified in these studies is innovative and high-risk, which makes tribology a vital and appropriate area for ECUT support. Thus the ECUT Tribology Program, with industry participation and cooperation, will continue its efforts to reduce the enormous energy losses caused by friction and wear.

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FIGURES

TABLES

SUMMARY

PURPOSE OF THE STUDY

This report assesses the energy conservation impact of surface modification technologies on the metalworking industries. It was prepared for the Energy Conversion and Utilization Technologies (ECUT) Division of the Department of Energy's Energy Systems Research Office. This report is part of the background data for ECUT's tribology research plan.

SCOPE OF THE STUDY

The energy conservation impact of surface modification technologies on the metalworking industries is assessed by estimating their friction and wear tribological sinks and the subsequent reduction in these sinks when surface modified tools are used.

Surface Modification Technologies Considered in This Study

Surface modification technologies are thermal, chemical, or mechanical treatments (or a combination thereof) that can impart tribologically superior properties to the surface of a material without changing its bulk properties.

This study considers only advanced surface modification technologies, namely, ion implantation, coatings, and laser and electron beam surface modifications.

The Metalworking Industries and Metalworking Machines Considered in This Study

All manufacturing industries that cut or form metals are considered. Metalworking and metalcutting associated with primary metals processing are not included, however, because they have been analyzed in another study.[a]

The metalforming machines considered are punches, presses, and forges. The metalcutting machines are turning, drilling, milling, broaching, and sawing machines. The study considered 326,587 metalforming machines, or 67 percent of all metalforming machines in the United States; it considered 1,215,780 metal-

(a) Imhoff, C. H., et al. 1985. A Review of Tribological Sinks in Six Major Industries. PNL-5535, Pacific Northwest Laboratory, Richland, Washington.

cutting machines, or 71 percent of all metalcutting machines in the country. Overall, the study considered 70 percent of all metalworking machines in the United States.

METHODOLOGY

The energy savings model developed to estimate the friction and wear tribological sink is shown in Figure S.1.

The frictional tribological sink is estimated as the sum of frictional losses at the motor drive system and at the tool-workpiece interface. The wear tribological sink is the embodied energy of all metalworking tools consumed and discarded in one year. The energy savings due to surface modification are equal to the tribological sink adjusted downward to take into account increased tool life and the reduction in friction due to surface modification. Such downward adjustments are made using known functional relations between the coefficient of friction and the work done to overcome friction during metalworking.

RESULTS

Tribological Sinks in Metalworking

Estimates for the tribological sinks in metalworking are shown in Table S.1.

The drive sink is defined as frictional losses at the drive system of the metalworking machines considered. The drive sink for a given machine is calculated as 20 percent of the total power output of its main drive motor.

The tool sink is defined as frictional losses at the tool-workpiece interface during metalworking. For metalcutting, the tool sink is calculated as 50 percent of the power delivered at the tool joint. For metalforming, the sink is calculated as 10 percent of the main drive motor output that is available to the metalforming process. The percentage values used (50 percent and 10 percent) are based on an analysis of the functional relations between the work done to overcome friction and the coefficient of friction in representative metalworking operations.

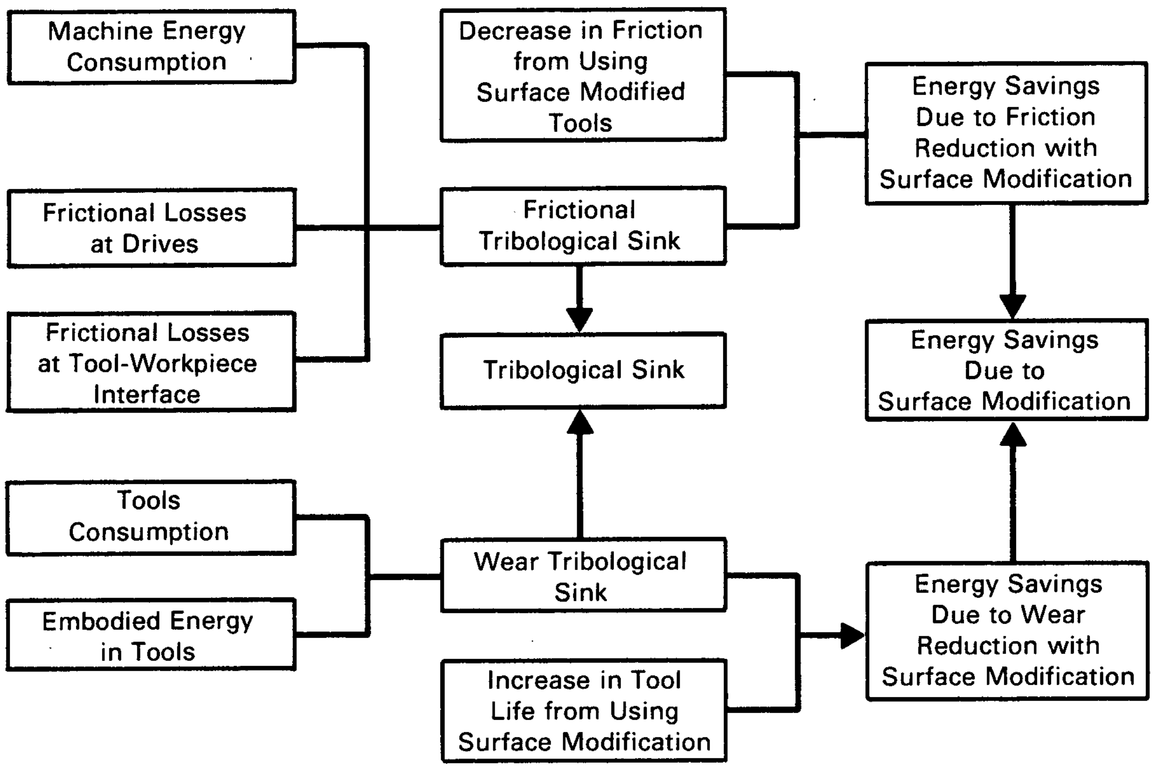


FIGURE S.1. Energy Savings Estimation Model

TABLE S.1. Tribological Sinks in Metalworking (billion Btu/year)

Operation	Frictional Sink Drive	Frictional Sink Tool	Wear Sink	Total
Metalcutting	2,490	3,320	2,323	8,133
Metalforming	10,400	4,000	5,370	19,770
Total	12,980	7,320	7,693	27,903

The wear sink is defined as the energy embodied in the steels that are used to manufacture metalworking tools, e.g., cutting tools, punches, and dies. The wear sink is calculated using estimated tonnages of the steels used to manufacture metalworking tools and an embodied energy figure of 19.2 million Btu/ton of steel.

ENERGY CONSERVATION IMPACT OF SURFACE MODIFICATION TECHNOLOGIES

Estimates of the energy savings achievable when surface modified tools are used in metalworking are shown in Table S.2.

Assuming an electricity purchase price of $12/million Btu, the dollar costs of tribological losses total $335 million/year; at the same time, the savings with use of surface modified tools would be $88 million/year (see Table S.3). Note that the dollar losses and savings are averaged over the whole country without regard to regional variations in energy costs.

TABLE S.2. Energy Conservation with Surface Modification Technologies (billion Btu/year)

Operation	Reduction in the Friction Sink: Drive	Reduction in the Friction Sink: Tool	Reduction in the Wear Sink	Total
Metalcutting	0	739 (22%[a])	1,936 (83%)	2,675 (53%)
Metalforming	0	1,100 (25)	3,580 (67)	4,680 (24)
Total	0	1,839 (25)	5,536 (72)	7,355 (26)

(a) Percent of the sink.

TABLE S.3. Dollar Values of Tribological Losses and Energy Savings Potential with Surface Modified Tools in Metalworking (million dollars/year)

Operation		Frictional Sink: Drive	Frictional Sink: Tool	Wear Sink	Total
Metalcutting:	Losses	29.9	39.8	27.8	107.5
	Savings	0	8.9	23.2	32.1
Metalforming:	Losses	124.8	48.0	64.4	237.2
	Savings	0	13.2	43.0	56.2
Cutting and Forming:	Losses	154.7	87.8	92.2	334.7
	Savings	-	22.1	66.2	88.3

ACKNOWLEDGMENTS

The research staff of this project would like to thank Carl Imhoff, PNL Technical Monitor for this project, for his guidance and support. We would like also to thank Sheila Mulvihill and Donna Kuick for providing editorial assistance and Judy Cable for producing the various draft reports. Finally, we extend our appreciation to John Brogan, Terry Levinson, and Manfred Kaminsky of the U.S. Department of Energy for their support throughout this project.

1.0 INTRODUCTION

Tribology, the science of surfaces in dynamic contact, is concerned with the phenomena of wear, friction, and lubrication. These phenomena are important to the conservation of energy. High friction reduces the energy conversion efficiencies of mechanical devices and processes; excessive wear increases the replacement rate of accessories and components, which have embodied energy costs of their own.

Modification of surfaces can reduce energy losses caused by tribological phenomena. Surfaces may be treated thermally, chemically, or mechanically -- or by a combination of technologies -- to impart tribologically superior properties to the surface of a material without changing its bulk properties.

This study assesses the impacts of surface modification technologies on tribological energy losses in metalworking operations. It was sponsored by the Energy Conversion and Utilization Technologies (ECUT) Division of the Office of Energy Systems Research in the Department of Energy's Office of the Assistant Secretary for Conservation and Renewable Energy. This study was sponsored as part of the ECUT R&D planning for the tribology component of its program.

1.1 BACKGROUND

1.1.1 The ECUT Program

ECUT supports long-term, high-risk, generic applied research and exploratory development pertinent to energy conservation. The four major goals of ECUT are to: (a) establish the feasibility of revolutionary concepts to reduce energy consumption significantly; (b) monitor and assess the applicability of advances in basic research to energy conservation; (c) carry out exploratory development of novel or innovative concepts; and (d) expand the technology base for advanced conservation technologies. To implement these goals, ECUT has been pursuing three programs: Combustion and Thermal Sciences, Materials Science, and Tribology. The Combustion and Thermal Sciences Program sponsors R&D activities in areas such as stratified charge combustion, diesel combustion, fluid flow in shell and tube heat exchangers, and dilute homogeneous charging. The Materials Science Program sponsors research in high-temperature,

light-weight, and innovative building materials and theoretical and experimental research in materials design. The tribology program sponsors research in base stock oil, friction and wear of ceramics, solid lubricants, and, because tribology is new to ECUT, tribology R&D planning.

1.1.2 ECUT Tribology R&D Planning

The ECUT tribology R&D planning process consists of identifying and quantifying the major tribological sinks, i.e., the industries, machines, or components in which energy losses through tribological phenomena are greatest; determining the tribological mechanisms operating at these sinks; and identifying the more promising tribological control technologies.

1.2 APPROACH

The energy savings attributable to surface modification technologies are defined as equalling the tribological sink adjusted downward to account for two surface modification-induced effects: the decrease in the coefficient of friction at the tool-workpiece interface and the increase in tool life. In metalworking, the tribological sink is defined conventionally as the sum of the energies lost directly through friction and indirectly through wear.

In implementing the above approach, DHR considered metalworking machines in groups rather than by individual machine type. Thus, metalcutting machines are classified as turning (e.g., turning and boring machines and machining centers), milling (e.g., milling and gear cutting machines), drilling (e.g., drilling and tapping machines), and sawing (e.g., cutoff and sawing machines, hacksaw and band sawing machines). Similarly, metalforming machines are classified as punching and shearing, bending and forming, and presses and forges.

For the estimates of energy consumption by each group of machines, conditions as realistic as possible are used. For example, for metalcutting machines, the total working time, the machining parameters (speed, feed, depth of cut) are chosen according to known standard conditions. In the same manner, tribological improvements attributable to surface modification technologies are taken from actual experimental or production setting data.

The computational facility is a spreadsheet program, specifically, the Lotus 1-2-3 software. It is ideal for repetitive calculations of the type performed in this study.

1.3 CHAPTER CONTENTS

Chapter 2 briefly reviews R&D and commercial activities in surface modification technologies, particularly the tribological improvements attributable to surface modified tools. Chapter 3 defines and describes the metalworking industries and operations considered in this study. Chapter 4 details the methodology used to estimate the metalworking tribological sinks and the energy savings attributable to the use of surface modified tools. Chapter 5 presents the results of the model implementation developed in Chapter 4, using the data compiled in Chapters 2 and 3.

2.0 THE TRIBOLOGICAL IMPACT OF SURFACE MODIFICATION TECHNOLOGIES

Surface modification technologies are thermal, chemical, or mechanical treatments (or any combination thereof) that can impart desirable properties to the surface of a material without affecting its bulk properties. Although heat treatment is used to build a hard, wear-resistant outer layer on a component, it is not included here because this study is focusing on innovative approaches. The surface modification technologies included are ion implantation, laser surface hardening, electron beam surface hardening, and coating deposition. Strictly speaking, coating is not a true surface modification technology. However, because coating is the principal commercial technique used to produce a very thin and tribologically superior surface on metalworking tools, coating deposition is also considered.

2.1 SURFACE MODIFICATION TECHNOLOGIES AND RELATED R&D ISSUES

2.1.1 Ion Implantation

2.1.1.1 Technology Status

Ion implantation involves the in-vacuo acceleration of ion species (such as the ions of Ti, Ta, Cr, Ni, N, Al) under a high voltage (typically up to 200 kV) onto the surface of a target workpiece. As these ions impact and penetrate the surface, they displace atoms from their equilibrium position, generate cascades of defects and compositional changes to a depth of 200 nanometers (nm), and thus create a surface layer that differs sharply from the bulk in terms of microstructure and properties.

The microstructures created by ion implantation are complex: most are formed through nonequilibrium transformation processes in a crystal lattice that has a very high defect density. Observed microstructures include supersaturated substitutional solutions, metastable crystalline and amorphous phases, complex defect clusters, and very fine precipitates. Properties that are enhanced by ion implantation include hardness, toughness, ductility, and resistance to friction, wear, adhesion, corrosion, fatigue, and oxidation (Refs. 1, 2).

Ion implantation is available commercially in the United States as a tribological surface treatment for metalworking tools by Zymet Incorporated, of Danvers, Massachusetts (Ref. 3). The Navy recently contracted with Spire Corporation of Bedford, Massachusetts, to investigate the benefits of ion implantation on ball bearing components and stamping and punching tools (Ref. 4). In the United Kingdom, Harwell has conducted case studies of the industrial application of nitrogen ion implantation in more than 100 companies since 1978 (Ref. 5).

2.1.1.2 Research Opportunities

Basic ion implantation research in the United States is supported by private industry and the government. The latter include the Naval Research Laboratory at the University of Virginia, the National Science Foundation at the University of Connecticut, and the Department of Energy at Oak Ridge National Laboratory (Ref. 6).

Basic research opportunities in ion implantation are numerous. Although the structure and properties of the ion implanted layers have been well characterized and to some extent correlated with implantation parameters, not all the microstructures found can be explained. Specifically, fine scale microstructural features such as the presence of amorphous and amorphous-to-crystalline transition phases (Ref. 7), the dislocation density, and precipitate size have not been consistently predicted (Ref. 8). Because many of the microstructural transformations in the ion implanted layer are nonequilibrium phenomena, research in nonequilibrium transformations as they relate to ion implantation will be needed. From a tribological perspective, any research that attempts to relate nonequilibrium microstructures to friction and wear reduction would be extremely relevant. Although such work on Ti, C, N, and Ta implanted steels has been initiated at the Naval Research Laboratory under the direction of Singer, much remains to be done. For example, understanding the nature and role of amorphous phases in the friction reduction mechanisms that operate in ion implanted layers is important because these phases must be present to lower the coefficient of friction (Ref. 1).

Other research opportunities also exist. Thus, ways to increase the penetration depth other than increasing the ion implantation beam energy are needed

because, at high beam energy, the inward diffusion of the implanted ion species is inhibited by the beam heating effects and radiation damages phenomena. Similarly, ways must be found to maximize multi-beam sequential ion implantation in order to prevent impacting ions' ejecting previously embedded ones out of the sample surface (Ref. 7).

2.1.2 Coating Deposition

2.1.2.1 Technology Status

Hard, wear-resistant coating compounds such as Al_2O_3, MfN, TiC, and TiN are deposited on a metalworking tools in a variety of ways. In chemical vapor deposition (CVD), a carrier gas (such as $TiCl_4$) is reacted with a reactive gas (such as N_2) in an evacuated and heated chamber to form a compound (TiN, in this case) on the workpiece. CVD is carried out at high temperatures, 1750-1950°F, so that reheat treatment for most tool materials would be needed. In basic physical vapor deposition (PVD), a high voltage existing between the workpiece (which acts as the anode) and the target (which acts as the cathode) causes the target atoms to be ionized and accelerated toward the workpiece, where they deposit to form the desired coating. Variations of the basic PVD process include reactive sputtering, in which a gaseous reaction similar to the one found in CVD takes place to form the coating compound; reaction ion plating, in which the target material is ionized in the presence of a reactive gas to form the ion species on the workpiece; and arc-evaporation, in which an arc is used to localize the CVD process over a small area. PVD is carried out at 500-900°F so that reheat treatment of the samples is not usually necessary.

The deposition of a hard, wear-resistant coating on metalworking tools is a big industry. Most small cutting tools and many forming dies and punches are now commercially available with a TiN coating (see Table 2.1). Many tool suppliers do the coating themselves or contract with a coating firm to have it done. Companies that supply CVD coating systems are the Sylvester Company (Beachwood, Ohio), which uses a process developed by Bennex (Switzerland); Ti-Coating Incorporated (Mt. Clemens, Michigan); and Scientific Coating Incorporated (Troy, Michigan). The PVD system suppliers are Balzer High-Vacuum Corporation (Hudson, New Hampshire), Multi-Arc Vacuum Systems Incorporated

TABLE 2.1. Major Suppliers of Coated Tools (Ref. 9)

Company	Location	Major Coated Product
American Broach	Ann Arbor, Michigan	Broaches
American Intertool	Elk Grove Village, Michigan	End Mill
American Pfauter	Elk Grove Village, Michigan	Hobs
Barber Colman	Rockford, Illinois	Hobs, Cutters of All Types
Cosa Corporation	Montvale, New Jersey	Hobs
Detroit Tap and Tool	Warren, Michigan	Tap, Thread Mill, Thread Gages
DoAll Company	Des Plaines, Illinois	End Mill, Band Saw Blades
Ekstrom, Carlson and Company	Rockford, Illinois	Router Bits
Fellows Corporation	Springfield, Virginia	Gear Shaper Cutters
General Broaches	Detroit, Michigan	Broaches
Guhring Broaches	Detroit, Michigan	Twist Drill, Reamers
Nachi America	Carlstadt, New Jersey	Hob, End Mills
Onsrud Cutter Manufacturing Company	Libertyville, Illinois	Milling Cutter, Router Bits
Start Cutter Company	Farmington Hills, Michigan	Hobs, Form Tools, Reamers
TRW Drill and End Mill Division	Augusta, Georgia	Twist Drill, End Mills
Valform	Troy, Michigan	T15 Inserts
Vermont Tap and Die Company	Lyndonville, Vermont	Taps, Drills
Waukesha Cutting Tools	Waukesha, Wisconsin	Spade Drill Blades

(St. Paul, Minnesota), and Ulvac North America Corporation (Kennebunk, Maine), which represents the Ulvac Corporation of Japan (Ref. 9).

Government support for coating research comes from many quarters. The Department of Energy sponsors research on cutting tool coatings at Argonne National Laboratory, high-temperature tribological coatings on ceramics at Lawrence Berkeley Laboratory, plasma-assisted low-temperature deposition of

cubic boron nitride and diamond-like coatings at Oak Ridge National Laboratory, and magnetron sputtering of amorphous coatings at Jet Propulsion Laboratory. The National Aeronautics and Space Administration Lewis Research Center has investigated the sputtering of silicon and hafnium nitrides on stainless steel and the morphology of plasma coating. The National Bureau of Standards (NBS) is considering the effects of coating on hardness and friction (Ref. 6).

2.1.2.2 Research Opportunities

Basic research needs and opportunities in tribological coatings are numerous. A major research area is the production of strong and highly adherent coatings. CVD-deposited TiN and HfN coatings generally have low adherence and fracture toughness because, at the high deposition temperatures involved, the coating microstructure is likely to consist of large grains and the cemented carbide substrates are attacked chemically (Ref. 10). Although proprietary CVD techniques to produce very fine grained microstructures have been developed (Ref. 11), a lower CVD process temperature to minimize subsequent heat treatment is desirable. The development of amorphous coatings is also a promising research area. However, it is being vigorously pursued by industry. In effect, two companies, Energy Conversion Devices, Inc. and Chronar, both amorphous photovoltaic cell producers, have announced plans to market metalworking tools with friction- and wear-resistant amorphous coatings. A second major research need is to relate coating microstructure and coating-substrate interactions to friction and wear reduction mechanism studies; little work, except the NBS effort cited above, has been done.

Two research areas have high energy conservation potential: development of low-temperature coating deposition processes and development of cubic boron nitride (CBN) coatings. A low-temperature coating process would minimize sample heating and eliminate the additional heat treatment to recover the optimum bulk properties. The development of a CBN coating would maximize the benefits of coatings because CBN is second only to diamond in hardness.

2.1.3 Laser and Electron Beam Surface Modification

2.1.3.1 Technology Status

In laser surface modification, a narrow, high-power laser beam is directed onto a metal surface where some of its energy is absorbed and converted into

heat. As the beam is scanned across the surface, extremely rapid and localized heating and cooling of the surface occurs along the path of the beam, thus producing the laser-modified layer. The depth of the laser-modified layer depends on the power of the laser, the duration of the laser pulse or the scan rate, and the optical and thermal properties of the materials. Typical depths are 100-200 nm. In laser surface alloying, alloying elements are introduced into the laser melted surface to produce a surface layer of an alloy that is an essentially different from the bulk.

The microstructures obtained in laser surface modification and surface alloying include dendritic and columnar dendritic structures, very fine precipitates, and metastable phases that are characteristic of rapidly solidified materials. With steels, a noteworthy feature of a laser processed surface is the formation of a metastable austenite phase that will later transform into a stable martensite phase, resulting in increased hardness and wear-resistance. This phenomenon is seen in laser processed cast iron (Ref. 12) and high speed steel saw blades (Ref. 13).

Laser surface modification is used extensively by the automotive industry to harden drive train components in order to reduce friction and wear. Government sponsors of laser surface modification research include the Office of Naval Research (ONR) and the National Science Foundation (NSF). ONR is funding research on laser CVD of TiC and laser surface alloying and cladding at the University of Illinois. NSF is supporting research on the wear behavior of laser transformed gray and ductile cast iron at Iowa State University (Ref. 6).

2.1.3.2 Research Opportunities

Research on laser surface modification is primarily concerned with relating the microstructure of the laser modified layer to the laser energy deposition parameters, e.g., the substrate material, the rate of energy deposition, beam dwell time, and heat transfer phenomena at the laser modified layer (Ref. 14). Although the laser produced surfaces are well characterized, the ability to control and allow for the formation of the desired microstructures is still lacking. From a tribological perspective, the problem of relating the microstructure of the laser modified layer to its tribological properties and the laser energy deposition conditions has not been addressed.

2.1.4 Electron Beam Surface Modification

Electron beam surface modification is similar to laser surface modification, except that an electron beam is used as the heat source and a vacuum is needed. Research needs and opportunities in electron beam surface modification are similar to those found in laser surface modification. Thus, it is not necessary to go into detail here, except to note that technology development in electron beam surface modification closely follows that of electron welding (Ref. 15).

2.2 THE TRIBOLOGICAL IMPROVEMENT ACHIEVED WITH SURFACE MODIFICATION TECHNOLOGIES

Reduction in friction and wear and development of a better surface finish are the direct tribological improvements achievable with surface modification technologies. Because results of laboratory friction and wear tests are generally not applicable to actual production settings and should be considered only as indicators of what can be achieved with surface modification technologies, this section concentrates on the experience of surface modified tool users.

2.2.1 Wear Reduction in Metalforming

Wear reduction is indicated indirectly by an increase in tool life or in the number of operations performed before retooling; wear can also be measured directly. Table 2.2 lists the increased wear life and additional benefits obtained by nitrogen implantation on a variety of metalforming applications. As shown, the average tool life increase is between 200 and 600 percent. The surface finish of the formed parts is generally better (Ref. 16).

2.2.2 Wear Reduction in Metalcutting

In drilling, the effects of TiN coatings of high-speed steel (HSS) drills have been considered by TRW's Drill and End Mill Division,[a] Vermont Tap and

(a) Personal communication with J. Bhardwag, TRW Cutting Tool Division, Augusta, Georgia.

TABLE 2.2. Wear Reduction in Metalforming Achieved with Nitrogen Implantation (Ref. 16)

Application	Tool Life Material	Increase	Other Benefits
Scoring Die for Aluminum Beverage Can Lids	D2 Tool Steel	3X	
Forming Die for Aluminum Beverage Can Bottoms	D2 Steel	3X	Markedly Lowered Material Pick Up
Wire Guides	Hard Cr Plate	3X	
Finishing Rolls for CU Rods	H-13 Steel	3X	Negligible Wear After 2X Normal Lifetime; Improved Surface Finish Products
Sheet Steel Chopper Blades	WC - Co	>3X	Reduced Chipping
Punch and Die Set for Sheet Steel Lamination	WC - Co	4-6X	Improvement Remains After Sharpening
Dies for Copper Rod	WC - 6% Co	5X	Improved Surface Finish
Dies for Steel Wires	WC - 6% Co	3X	

Die Company (Ref. 17), and Guhring Incorporated (Ref. 9). Conservatively, an average 600 percent increase in tool life can be expected with a TiN coating (see Table 2.3).

In milling and gear cutting, Barber-Colman Incorporated found an 800 percent increase in hob life with TiN coated tools; Fellows Corporation, a 400 percent increase (Ref. 9); and the DoAll Company, between 600 and 900 percent (Ref. 18). The average increase in tool life in milling and gear cutting is 600 percent.

In tapping, Vermont Tap and Die Company reported a 400 percent increase in tap life when the tap was coated with TiN (Ref. 17).

2.2.3 Friction Reduction in Metalforming

Actual data on a reduction in the coefficient of friction due to the use of surface modified tools in metalforming are not generally available. In a drawing experiment that compared carbide dies to sapphire (Al_2O_3) dies, Wright noted a 7 percent decrease in the effective coefficient of friction, from 0.084 to 0.078 (Ref. 19). If sapphire dies can be taken as an approximation of the TiN or similar surface modified layers on a tool, a reduction in the coefficient of friction of the same order of magnitude should be expected from surface modified tools.

2.2.4 Friction Reduction in Metalcutting

Actual data on a reduction in the coefficient of friction due to the use of surface modified tools are also not available. Henderer, of Vermont Tap and Die Company (Ref. 8), noted that in drilling with TiN coated tools, torque and thrust were lowered by 34 percent and 43 percent, respectively, when compared to uncoated drills. Deller, of TRW Drill and End Mills Division (Ref. 9), also

TABLE 2.3. Tool Life Increase in Drilling with TiN Coated Drills

Company	Life Increase	(Low)	(High)
TRW Drill and End Mill Division	7%	(1.5%)	(25%)
Vermont Tap and Die Company	6	(13.0)	(17)
Guhring Incorporated	5	(12.0)	(9)

measured a 25-35 percent reduction in both feed force and spindle torque when TiN coated drills were used. Because a reduction in torque directly reduces spindle horsepower, this study assumes that the work done to overcome friction is also reduced by the same amount, i.e., about 30 percent.

REFERENCES

1. Hubler, G. K. et al., eds. 1984. Ion Implantation and Ion Beam Processing of Materials. North Holland Publishing Company, New York.

2. Picreaux, S. T. and W. J. Choyke, eds. 1984. Metastable Materials Formation by Ion Implantation. North Holland Publishing Company, New York.

3. Savage, J. E. 1984. Metal Progress, 126(6):41.

4. 1981. American Machinist. 129(9):63.

5. Hartley, N. E. W. 1978. Ion Implantation Case Studies - Manufacturing Applications. Harwell Report AERE-R9065, Harwell, London, England.

6. Peterson, M. B. 1985. Assessment of Government Tribology Programs. PNL-5539, Pacific Northwest Laboratory, Richland, Washington.

7. Potter, D. I. et al. 1983. J. Metals. 35(8):17.

8. Schulson, E. M. 1980. Phil. Mag. 42(4):463.

9. Hatschek, R. L. March 1983. "Coatings: Revolution in HSS Tools," American Machinist Special Report. Volume 752.

10. Kodama, M. and R. E. Bunshah. 1982. Thin Solid Film, 96(1):Volume 53.

11. Stiglish, J. J. and R. A. Hetz. 1982. Ceram. Eng. Sci. Proc. 3(8):414.

12. Chen, C. H. et al. "Wear of Laser Processed Cast Iron," preprint.

13. Ahman, Leif. 1984. Met. Trans. A. 15A(10):1829.

14. Mukherjee, K. and J. Mazumder, eds. 1981. Lasers in Metallurgy. Metallurgical Society of AIME, Warrendale, Pennsylvania.

15. Steimetz, J. D. 1984. "Precision Electron Beam Heat Treating." Paper presented at the 2nd Biennial International Machine Tool Technical Conference, September 5-13, 1984. Chicago, Illinois.

16. Kirvonen, J. K. 1983. "Industrial Application of Ion Implantation." Paper presented at the Materials Research Meeting, November 1983. Boston, Massachusetts.

17. Henderer, V. 1983. "Performance of Titanium High Speed Steel Drills." Paper presented at the 11th North American Metalworking Research Conference, University of Wisconsin, May 24-26, 1983. Madison, Wisconsin.

18. DoAll Company, product literature. DoAll Company, 254 Laurel Avenue, Des Plaines, Illinois 60016.

19. Wright, P. K. and R. S. Rao. 1983. "Friction Reduction in Machining and Forming." Paper presented at the 11th North American Metalworking Research Conference, University of Wisconsin, May 24-26, 1983. Madison, Wisconsin.

3.0 THE METALWORKING INDUSTRIES

3.1 DESCRIPTION OF THE METALWORKING INDUSTRIES

The industries responsible for most of the metalcutting and metalforming activities in the United States are concentrated in the Standard Industrial Classification (SIC) groups 25 and 33-39 (Ref. 1). They are essentially the metal processing industries of the manufacturing sector (SIC code 3) of the economy. The economic importance of the metalworking industries is large, perhaps disproportionate to their size. Their energy consumption is significant. Their product line includes almost every metal-containing artifact of an industrial civilization; yet they use only about a dozen or so basic metalworking processes.

3.1.1 Nature of the Metalworking Industries

The metalworking industries are defined here as those whose operations include metalcutting and metalforming. Appendix A lists these industries according to the SIC 4-digit classification scheme, so that the major types of products are also shown. The major metalworking industry groups are SIC Group 25, Furniture and Fixtures; Group 33, Primary Metals; Group 34, Fabricated Metal Products; Group 35, Machinery Except Electrical; Group 36, Electrical and Electronic Equipment; Group 37, Transportation Equipment; Group 38, Instrument and Related Products; and Group 39, Miscellaneous Manufacturing Industries. Not all the industry groups listed are engaged primarily in metalworking - for example, Group 36, Electric and Electronic Equipment, is certainly not a pure metalworking industry although it processes a large volume of sheet metals. But all do have a substantial investment in metalworking machinery and equipment, and for this reason, they are included here.

The products manufactured by the metalworking industries include nearly all metal products necessary to an industrial society. A partial list of the more important ones includes ferrous and non-ferrous metal rolls, sheets, plates, bars, and shapes; structural metals for bridges and buildings; metalworking machine tools and accessories; cars, trucks, airplanes, and other transportation equipment; and most household appliances.

3.1.2 The Economic Importance of the Metalworking Industries

The metalworking industries employed about 6 million production workers and contributed nearly $313 billion to the national income in 1981 (Ref. 2). Table 3.1 provides income and employment data on these industries. The contribution of the metalworking industries to the national income and employment picture is important. With about 10 percent of the total employment, they accounted in 1981 for more than 42 percent of the total national income from the non-agricultural private sector, which comprises the mining, construction, and manufacturing industries.

3.1.3 Energy Consumption in the Metalworking Industries

To contribute $313 billion to the national income, the metalworking industries purchased 3.6 quadrillion Btu (or quads) of electricity and fuels for $20.2 billion in 1981 (Ref. 3). Table 3.2 shows the purchased electricity and fuel consumed for heat and power by the metalworking industries in 1981. The major energy consumers are the Primary Metals Industries, first, with 2.24 quads; the Fabricated Metal Products Industries, a distant second, with 0.35 quad; the Transportation Equipment Industries, third, with 0.33 quad; and the Machinery Except Electrical Industries, fourth, with 0.32 quad.

Not all of the 3.25 quads is used in metalworking exclusively; the industries considered also include the producers of primary metals and alloys from ores and scrap metals. Table 3.3 shows the electricity and fuels consumption of these primary metals and alloys producers. As shown, their combined energy use is approximately 1.4 quads. Subtracting this amount reduces the energy used in metalworking operations to 1.8 quads. The 1.8 quads figure is the target energy consumption that surface modification technologies seek to reduce through their application to metalworking machines.

3.2 MACHINERY AND EQUIPMENT IN THE METALWORKING INDUSTRIES

Metalworking machines are used either for metalcutting or metalforming. The major types of metalcutting machine tools are turning, boring, drilling, milling, grinding, cutoff and sawing, broaching, and finishing machines. The major types of metalforming machine tools are punching and shearing machines, bending and forming machines, and presses and forges.

TABLE 3.1. Income and Employment in the Metalworking-Intensive Industries, 1981

SIC	Description Group	Contribution to the National Income[(a)] (billions of dollars)	Employment: All Employees (1000)	Employment: Production Workers (1000)
25	Furniture and Fixtures	8.4	467	376
33	Primary Metal Products	43.3	1121	861
34	Fabricated Metal Products	44.8	1592	1173
35	Machinery, Except Electrical	75.7	2507	1585
36	Electrical, Electronic Equipment	53.6	2091	1312
37	Transportation Equipment	57.9	1900	1216
38	Instruments, Related Products	20.1	727	428
39	Miscellaneous Industries	9.1	407	304
	Total	312.90	10812	7255
	Percent of All Manufacturing	53.9%	44.2%	43.1%
	Percent of All Non-Agricultural Industries	42.3%	9.8%	6.7%

(a) Not adjusted for capital consumption.

Source: U.S. Bureau of the Census, Statistical Abstract of the United States 1982-83, 102d edition, Washington D.C.

TABLE 3.2. Purchased Fuel and Electricity Consumption for Heat and Power by Major Metalcutting and Metalforming Industries, 1981

SIC Code	Industry Group and Industry	Electricity: Purchased (million kWh)	Electricity: Generated Less Sold (kWh)	Purchased Fuels (trillion Btu)	Purchased Fuels and Electric Energy (trillion Btu)
25	Furniture and Fixtures	4,143.2	(S)[a]	32.0	46.2
251	Household Furniture	2,539.8	(S)	17.1	25.7
252	Office Furniture	499.2	(D)[b]	4.5	6.2
2531	Public Building and Related Furniture	213.7	(D)	2.0	2.7
254	Partition and Fixtures	651.7	--[c]	5.9	8.1
259	Miscellaneous Furniture and Fixtures	238.7	--	2.6	3.4
33	Primary Metal Industries	165,959.4	9,058.0	1,674.4	2,240.6
331	Blast Furnace and Basic Steel Products	59,520.4	5,441.2	1,192.3	1,395.4
332	Iron and Steel Foundries	11,618.9	(S)	115.2	154.9
333	Primary Non-Ferrous Metals	78,465.6	(S)	165.1	432.8
3341	Secondary Non-Ferrous Metals	1,033.2	(D)	35.3	38.8
335	Non-Ferrous Rolling and Drawing	11,458.4	(S)	113.5	152.6
336	Non-Ferrous Foundries	2,337.7	(D)	31.0	39.0
339	Miscellaneous Primary Metal Products	1,524.4	--	21.9	27.1
34	Fabricated Metal Products	25,539.1	(S)	264.7	351.9
341	Metal Cans and Shipping Containers	2,183.8	(D)	22.4	29.8
342	Cutlery, Hand Tools and Hardware	2,396.9	(D)	20.4	28.5
343	Plumbing and Heating, Except Electric	723.4	(D)	8.3	10.8
344	Fabricated Structural Metal Products	5,129.2		6.5	48.766.2
345	Screw Machine Products, Bolts, etc.	1,601.6	(D)	13.3	18.7
346	Metalforging and Stamping	5,528.1	(S)	73.4	92.3
347	Metal Services N.E.C.	2,019.9	17.9	32.4	39.3
348	Ordnance and Accessories	1,454.1	(D)	12.8	17.8
349	Miscellaneous Fabricated Metal Products	4,502.0	(S)	33.2	48.5
35	Machinery, Except Electrical	31,569.1	126.9	2127.1	324.8
351	Engines and Turbines	2,597.3	21.6	21.6	30.4
352	Farm and Garden Machinery	2,055.7	(D)	24.1	31.1
353	Construction and Related machinery	5,764.6	23.6	48.2	678.9
354	Metalworking ,Machinery	3,860.0	6.7	22.5	35.7
355	Special Industry Machinery	1,930.6	(D)	14.4	21.0
356	General Industry Machinery	4,932.5	(S)	34.9	51.7
357	Office and Computing Machines	4,553.6	(D)	10.8	26.4
358	Refrigeration and Service Machinery	2,644.8	0.1	21.0	30.0
359	Miscellaneous Machinery, Except Electrical	3,230.2	(D)	19.6	30.7

TABLE 3.2. (contd)

SIC Code	Industry Group and Industry	Electricity: Purchased (million kWh)	Electricity: Generated Less Sold (kWh)	Purchased Fuels (trillion Btu)	Purchased Fuels and Electric Energy (trillion Btu)
36	Electric and Electronic Equipment	28,027.0	38.8	139.4	235.0
361	Electric Distributing Equipment	1,490.8	(D)	9.7	14.8
362	Electrical Industrial Apparatus	4,534.3	(D)	26.6	42.1
363	Household Appliances	2,391.4	(S)	23.9	32.0
364	Electric Lighting and Wiring Equipment	2,288.6	(S)	17.5	25.3
365	Radio and TV Receiving Equipment	897.3	(D)	5.4	8.4
366	Communication Equipment	5,611.4	(D)	19.1	38.2
367	Electronic Components and Accessories	8,262.4	(S)	24.3	52.5
369	Miscellaneous Electrical Equipment and Supply	2,550.7	(D)	13.0	21.7
37	Transportation Equipment	30,090.5	(S)	226.4	329.1
371	Motor Vehicles and Equipment	16,983.2	(D)	145.7	203.7
372	Aircraft and Parts	7,689.7	(S)	41.3	67.5
373	Ship and Boat Building and Repairing	2,345.1	(S)	15.2	23.2
3743	Railroad Equipment	735.2	(D)	11.8	14.3
3751	Motorcycles, Bicycles and Parts	196.6	--	1.8	2.5
376	Guided Missiles, Space Vehicles, Parts	1,790.9	(D)	6.6	12.8
379	Miscellaneous Transportation Equipment	349.8	--	3.9	5.1
38	Instruments and Related Products	6,127.5	(D)	57.6	78.5
3811	Engineering and Scientific Instruments	381.7	--	1.8	3.1
382	Measuring and Controlling Devices	2,018.7	(S)	8.2	15.1
3832	Optical Instruments and Lenses	415.5	(D)	1.6	3.0
384	Medical Instruments and Supplies	1,372.7	(D)	7.7	12.3
3851	Opthalmic Goods	255.5	(D)	2.0	2.9
3861	Photographic Equipment and Supplies	1,516.0	(D)	35.4	40.5
3873	Watches, Clocks and Watchcases	167.5	--	1.0	1.5
39	Miscellaneous Manufacturing Industries	3,630.8	14.4	30.8	43.2
391	Jewelry, Silverware and Plated Wire	321.6	(D)	2.2	3.3
3931	Musical Instruments	208.2	--	1.3	2.0
394	Toys and Sporting Goods	1,184.9	(D)	8.6	12.6
395	Pens, Pencils, Office and Art Supplies	360.9	--	2.0	3.2
396	Costume Jewelry and Notions	369.1	(D)	2.4	3.6
399	Miscellaneous Manufactures	1,187.1	(D)	14.3	18.4
	Total All Industries	295,108.6	--	2,642.4	3,649.3

(a) (S)--withheld because estimate did not meet publication standards on the basis of either the response rate or a consistency review.
(b) (D)--withheld to avoid disclosing data for individual companies.
(c) --indicates zero

Source: U.S. Bureau of the Census 1982, Census of Manufacturers, June 1983.

TABLE 3.3. Non-Metalworking Energy Uses in the Metalworking-Intensive Industry Group SIC 33

SIC Code	Industry	Purchased Fuel and Electricity (Trillion Btu)
3312	Blast Furnace and Steel Mills	644.4[a]
3313	Electrometallurgical Products	54.8
332	Iron and Steel Foundries	154.9
333	Primary Non-Ferrous Metals	432.8
335	Non-Ferrous Foundries	39.0
339	Miscellaneous Primary Metal Products	27.1
	TOTAL	1353.0

(a) This is 50% of the total purchased fuel and electricity used in Industry 3312. Fifty percent is approximately the ratio of energy used in refining to that used in finishing (e.g., rolling, drawing) in an integrated steel mill.

Source: U.S. Bureau of the Census, 1982 Census of Manufacturers (MC82-5-4, Part 1), June 1983.

Of interest to this study are statistics on the number of machine tools in use in the United States and data on the horsepower of the spindle drive of the machines. The horsepower data are important because the horsepower (watts) multiplied by the operation time (hours) provides an estimate of the energy consumption (kWh) of a machine. Statistics have been compiled by the Machinist Information Service in its 13th American Machinist Inventory of Metalworking Equipment 1983 (Ref. 4). DHR surveyed the spindle horsepower of machine tools using machine specification data supplied by machine tool manufacturers. The results of the survey are given in Appendix B. The major metalworking machine tools are described below.

3.2.1 Metalcutting Machines and Accessories

3.2.1.1 Turning Machines

Turning machines remove metal from the surface of a rotating workpiece through the action of a cutting tool pressed against it. Turning is done on a

lathe. Turning lathes are classified according to chuck size (usually up to 20"), function (tracer or toolroom, turn, or turn and bore), spindle orientation (vertical or horizontal), or the number of spindles (one or more). The power rating of the electric motor drive of a turning machine spindle ranges from 4 to 150 horsepower (hp). Turning machines and most metalcutting machines are usually also equipped with several fractional horsepower motors to circulate the coolant and the lubricant or to assist in positioning the workpiece.

Turning tools can be single point, box, form, or cutoff tools and cutting inserts. The major types of tool materials are high speed steels, carbides, and ceramics. Except for ceramic tools, all turning tools are amenable to surface modification to increase hardness and wear resistance.

In 1983, there were approximately 366,000 turning machines in use in the United States. Nearly one-half were used by Industry Group SIC 35, Machinery Except Electrical.

3.2.1.2 Boring Machines

Boring mills are designed to enlarge or finish holes in a workpiece using a rotating and cutting motion of a boring tool. Boring machines are usually classified according to spindle orientation (horizontal, vertical, or both; some spindles can be rotated about a center) or the degree of precision afforded (precision boring mills can position and bore to a few thousandths of an inch; jig boring mills need a fixture to position the workpiece). Boring tools are essentially similar to cutting tools in both design and material. The rating of the main spindle drive motor in boring machines varies from 8 hp to 120 hp.

In 1983, there were approximately 45,000 boring machines in the United States. Nearly one-half of them were used by Industry Group SIC 35.

3.2.1.3 Drilling Machines

Drilling machines produce holes in solid metal, usually with a rotary end cutting tool. Metal is removed as the rotating end cutter penetrates the workpiece and cuts the metal with its lips. As with turning or boring machines, drilling machines are also classified according to spindle orientation, the degree of precision afforded, or the type of hole drilled (deep hole drilling,

as needed for gun barrels, versus small hole drilling). Drilling machines' drive motors are comparable to boring machines', in the 8-120 hp range. The most common have a vertical or upright spindle. Most are equipped with a 15 hp spindle drive motor.

Drills vary in shape and size. They can be simple jobber, low helix, high helix, straight shank oil hole, three flute core, left hand, straight flute, step, or subland drills. Drill materials are high speed steels or carbides, the two major cutting tool materials. All HSS drills can be surface modified.

There were nearly 300,000 drilling machines in the United States in 1983; approximately one-third were used in SIC Group 35, Machinery Except Electrical.

3.2.1.4 Milling Machines

The rotating multiple tooth cutter of a milling machine produces surfaces of almost any orientation on a workpiece. The desired orientation is obtained by using the appropriate cutter tooth size and adjusting the relative orientation and direction of motion of both the cutter and the workpiece. Milling machines are classified according to spindle orientation (vertical or horizontal), design (knee and column or bed), or application (general purpose, profiling, duplicating). Most milling machines have spindle drive motors rated from 3 to 30 hp.

Milling cutters are classified as peripheral or end, depending on the location of the cutting teeth. Specialized milling cutters, such as slotting and sawing cutters, and inserts are also available. Materials for milling cutters are high speed steel and carbides. All HSS drills can be surface modified.

The number of milling machines in the United States was approximately 234,000 in 1983. Again, one-half were used by SIC Group 35.

3.2.1.5 Grinding Machines

Grinding machines remove materials from the surface of a workpiece using the abrasive wear action of a rotating grinding wheel. High friction coefficients are desirable in grinding. Grinding machines are classified according to purpose (precision, for a specific surface finish, or non-precision, for

stock removal without regard to surface finish) or the geometry of the desired surface (cylindrical for curved or round surfaces and surface for planes). The spindle drive of grinding machines can range from fractional horsepower (hp) for hand grinding of cutting tools in the shop to 50 hp for large parts.

Grinding is done using abrasive wheels, loose abrasives, or abrasive grinding belts. Typical abrasive materials are aluminum oxides, silicon carbides, and diamond particles. Because none of these materials is likely to be amenable to surface modification, at least in powder form, grinding machines are not considered for surface modification technologies in this study.

3.2.1.6 Cutoff and Sawing Machines

Cutoff and sawing machines use thin abrasive wheels or toothed metal blades and bands that rotate or reciprocate at a high speed to chip metal from the workpiece in a deep, narrow line, thus cutting the workpiece with a minimum of material removal, applied force, and power. Cutoff and sawing machines are classified according to cutting device type (abrasive wheel or saw) or motion (hacksaws reciprocate, band saws cut with a continuous motion of the blade). The spindle motor drive of cutoff and sawing machines ranges vary widely. The smallest have fractional horsepower motors; a few of the larger models have motors rated at up to 150 hp; the average horsepower value for sawing machines is around 5 hp.

Cutoff and sawing tools are hacksaw blades, band saws, circular saw blades, and abrasive wheels. Except for the abrasive cutoff wheels, which are bonded abrasive particles, and carbide insert tooth saws, all other cutoff and sawing tools are surface modifiable because they are made of carbon steels, alloy tool steels, and high-speed steels.

There were approximately 170,000 cutoff and sawing machines in the United States in 1983. About one-third were used by the Industry Group SIC 35.

3.2.1.7 Broaching Machines

Broaching machines remove materials on the surface of a hole to enlarge it by the cutting action of a broach, i.e., a tapered cutting tool with many transverse cutting edges, that is pushed or pulled, small end first, through the hole. Broaching machines are classified according to the direction of

travel of the broach (horizontal or vertical), the type of broaching operation (external for surface broaching and internal for hole broaching), or the drive (mechanical, hydraulic, pneumatic). Broaching machines are rated in tons, e.g., 5 tons, 10 tons, up to 50 tons, with 15-20 tons the average size. The motor drive of broaching machines is similar to that of presses of comparable tonnage rating, i.e., from 10 to 50 hp.

Broaching tools are either solid or shell broaches. Some broaches have carbide inserts or rings as cutting edges. The most commonly used broach materials are the high-speed steels, which are readily amenable to surface modification.

Broaching is a highly specialized operation, and the number of broaching machines in the United States is relatively low, nearly 16,000 in 1983. The Industry Groups SIC 35 (Machinery Except Electrical) and SIC 37 (Transportation Equipment) use about one-third of these machines each.

3.2.1.8 Finishing Machines

Finishing machines are specialized equipment such as honing and lapping machines. Metal removal, and therefore the power required, is minimal because the purpose of the operation is to finish machining the workpiece to the desired dimensions. In honing, the abrasive action of a honing stone is applied lightly and is usually set to rotate and reciprocate at the same time that it removes a very thin (a few thousandths of an inch) layer from the workpiece surface. In lapping, loose or bonded abrasive particles are used to polish the workpiece surface to extreme accuracy and finish dimensions. Honing and lapping machines have motor drives ranging from 0.25 hp to 10 hp.

The tools for finishing machines are abrasive wheels as well as loose abrasive and honing stones. These tools are not likely to be surface modifiable, and thus finishing machines are not considered in this study.

3.2.2 Metalforming Machines

3.2.2.1 Punching Machines

Punching machines use a die to cut shapes from metal sheets, plates, or strips in one or more strokes, or punches, of the die. Punching machines are

essentially presses designed for a particular type of punching operation. Most punch presses are mechanical. The major types of punching machines (and operations) are blanking, parting, piercing, notching, lancing, and trimming. In blanking, a shape is cut out of a metal sheet in a single stroke of the die. In parting, a thin strip of material is cut between two blanks to separate them. In piercing, holes are punched in sheet metal. In notching, metal at the edge of the strip or the blank is punched out. In lancing, a line is cut without severing any material from the metal strip, usually as preparation for bending or other subsequent forming operations. In trimming, excess metal is punched out. A punching machine can perform more than one punching operation.

The basic tool for punching is a mating punch and die set. Steel rule and template dies are commonly used. In a steel rule die set, the punch consists of an HSS or carbon steel strip that is edge-mounted in order to outline the shape to be cut on a piece of steel-backed plywood; the die is a plate of carbon or alloy steel with a hole of the same shape as the part to be punched. In a template die, the punch is a plate of alloy or tool steels in the shape of the part to be punched; the die is assembled from strips of the same material as the punch in such a way that the punch fits into it.

Punches and dies are designed to perform a certain number of production runs, from a few hundred to 100,000. Edge wear is a major cause of premature die failure. Because most punches and dies are made of steels (carbon, alloys, HSS), surface modification of edges would help reduce friction and wear.

Mechanical punch presses are usually powered by an electric motor. The motors range from 0.5 to 25 hp, with the average around 15 hp. Like most other forming machines, most punching machines are run continuously in a high-volume production setting. The number of punching machines in the United States was about 73,000 in 1983; one-third were in use in Industry Group 34, Fabricated Metal Products.

3.2.2.2 Shearing Machines

Shearing machines (or shears) cut sheet, plate, or strip metals using cutter blades. The shearing process is complete when the upper movable blade has penetrated the stock to a depth that is sufficient to cause the remaining

unpenetrated portion of the stock to fracture and separate. Triangular, square, or rectangular shapes are obtained using a straight blade shearing machine. Rotary shearing machines cut curved contours using a set of tapered revolving circular cutters. Shear blades and rotary cutters of most shearing machines are mechanically actuated; hydraulic or pneumatic shears are also used.

Shear blades are made from tool steels, carbon, or alloy steels. Blade edges are often hard faced. Edge inserts are also used. Most shear blades are designed for high-volume production. Like punching machines, shearing machines are powered by electric motors rated on the average at 15 hp. In 1983, there were 38,000 shears in the United States, about one-third of them in use in Industry Group 34, Fabricated Metal Products.

3.2.2.3 Bending and Forming Machines

Bending and forming machines are used to bend and form bars, tubes, and wires. A piece of stock is bent by a die clamp that presses it against a rotating form (draw bending) or that whips it against a fixed form or by a three roll arrangement in which two rolls support the stock and a third roll bends it. In the bending of tubings, mandrells are used to prevent tube collapse.

Bending and forming tools are forms, dies, and mandrells. The materials used for bending tools are hardened tool and low carbon steels for high-production runs and wood or aluminum if the stock is soft or only a few samples are made.

Bending machine types include press brakes, bending rolls, rotary bending and forming machines, and bending presses. Approximately one-third of the 77,000 bending machines in the United States in 1983 were used in Industry Group 34, Fabricated Metal Products.

Friction in bending is minimal. Because most tube forming operations, such as tube flaring and flanging, rely on frictional forces to shape the metal, bending and forming machines are not considered in this study.

3.2.2.4 Presses and Forges

Presses are used primarily for forming thin section stock, such as sheet metals and plates, while forges are used for heavy section stocks such as billets and slabs. These machines are essentially similar in design, but forges are much bigger and are capable of higher capacity or tonnage rating. Metal is formed with presses and forges by punching on the stock over a mating die. The ram to which the punch is mounted is actuated hydraulically, mechanically, pneumatically, or by gravity as in drop hammer forges.

Many design options for presses and forges exist. Table 3.4 shows some of them.

Forging machines are classified as open or closed die. In closed die forging, the flow of the workpiece metal is confined within the die; in open die forging, it is not. Within each type of forge, one can have hammers (drop, counterflow) or presses.

The basic forging and pressing tools are punches and dies. The properties of the alloys to be formed, the working temperature, the number of parts to be produced, and the past production rate are the major considerations in selecting tool materials. Common tool materials are hardened alloy and tool steels with good strength, hot hardness, and resistance to abrasion.

The rams and punches of presses and forges are driven directly or indirectly by electric motors. These motors lift the hammers, pressurize the fluids in accumulators for subsequent release at the ram at a high rate, or drive the punch directly using a variety of drive mechanisms. Thus, although a hydraulic press may be rated at 500 tons, it could be powered by just one 25 hp electric motor. Motors used in forges and presses are rated from 10 to 150 hp. For upset forging machines, for example, the average motor rating varies from 10 hp to a rated forging capacity of 125 tons to 150 hp at 1,800 tons. In 1983, there were approximately 280,000 presses and forges in the United States, about one-third of them used by Industry Group 34, Fabricated Metal Products.

TABLE 3.4. Characterization of 18 Types of Presses (Ref. 5)

	Type of Frame							Position of Frame				Action			Method of Actuation		
Type of Press	Open-Back	Gap	Straight-Side	Arch	Pillar	Solid	Tie Rod	Vertical	Horizontal	Inclinable	Inclined	Single	Double	Triple	Crank	Front-to-back Crank	Eccentric
Bench	X	X				X		X		X	X	X			X		X
Open-Back Inclinable	X	X				X		X		X		X	X		X		X
Gap-Frame	X	X				X	X	X	X	X	X	X	X		X	X	X
Adjustable-Bed Horn		X				X		X				X			X		X
End-Wheel		X				X		X				X				X	X
Arch-Frame				X	X		X		X			X	X			X	
Straight-Side			X	X		X	X	X	X		X	X	X	X	X	X	X
Reducing	X	X	X			X	X	X	X			X			X		
Knuckle-Lever			X			X	X	X			X	X	X				
Toggle-Draw			X			X	X	X					X	X	X		X
Cam-Drawing	X	X	X			X	X	X		X			X		X		
Two-Point Single-Action		X	X			X	X	X			X	X			X		X
High-Production			X			X	X	X			X	X			X		X
Dieing Machine					X			X				X			X		
Transfer		X	X			X	X	X				X			X	X	X
Flat-Edge Trimming				X		X		X					X				
Hydraulic		X	X		X		X	X	X	X		X	X	X			
Press Brake	X	X				X		X				X			X		

	Method of Actuation (contd)					Type of Drive				Suspension			Ram		Bed		
Type of Press	Toggle	Screw	Cam	Rack and Pinion	Piston	Over Direct	Geared, Over-drive	Under Direct	Geared, Under-drive	One-Point	Two-Point	Four-Point	Single	Multiple	Solid	Open	Adjustable
Bench		X		X	X	X				X			X		X	X	X
Open-Back Inclinable			X		X	X	X			X	X		X	X		X	
Gap-Frame	X				X	X	X			X	X	X	X	X	X	X	
Adjustable-Bed Horn					X	X	X			X	X		X		X	X	X
End-Wheel						X	X			X			X		X	X	
Arch-Frame							X	X			X			X			X
Straight-Side				X	X	X	X	X	X	X	X	X	X	X	X	X	
Reducing					X	X	X			X			X			X	
Knuckle-Lever	X					X	X			X	X		X	X	X	X	
Toggle-Draw	X						X		X	X	X	X		X		X	
Cam-Drawing			X			X	X			X				X		X	
Two-Point Single-Action							X		X		X		X		X	X	
High-Production						X	X			X	X		X			X	
Dieing Machine						X		X		X	X		X			X	
Transfer	X					X	X				X		X			X	
Flat-Edge Trimming			X				X			X			X				

REFERENCES

1. Office of Management and Budget. 1972. Standard Industrial Classification Manual. U.S. Government Printing Office, Washington, D.C.

2. U.S. Bureau of the Census. 1983. Statistical Abstract of the United States, 1982-83. 102nd ed. U.S. Government Printing Office, Washington, D.C.

3. U.S. Bureau of the Census. June 1983. 1982 Census of Manufacturers. MC82-S-84 (Part 2), Government Printing Office, Washington, D.C.

4. American Machinist. November 1983. The 13th American Machinist Inventory of Metalworking Equipment. American Machinist, McGraw-Hill Inc., New York.

5. Schey, J. A., ed. 1972. American Deformation Processes, Friction and Lubrication. 2nd ed. Marcel Dekker, Inc., New York.

4.0 ENERGY CONSERVATION IMPACT MODELING

The model used to assess the impact of surface modification technologies on energy uses in metalworking is described in this section. It is a simple model. From an estimate of the tribological sink in the metalworking industries and known data on the reduction in friction and wear achievable with surface modified tools, the energy which can be conserved by using these tools is derived.

4.1 ANALYSIS OF ENERGY USE IN METALWORKING

Metalworking-related energy uses can be classified as either direct or indirect. Energy is expended directly to deform and fracture the workpiece, overcome friction at the tool-workpiece interface, and operate the support systems of the machine tool during metalworking. Indirect energy uses can be classified as machine-, as manufacturing system-, or as economy-specific. Machine-specific energy uses are the embodied energies in worn tools and other consumables and the energy used by the machine itself when it is idling. Manufacturing system-specific energy uses are those changes in energy use in the manufacturing system (of which the machine tool is a part) that are traceable to changes in metalworking conditions at the machine tool itself. Economy-specific energy uses are changes in the total energy use of the economy as a whole that are traceable to the quality of the metalworked product. Table 4.1 lists these types of energy uses and shows the probable effects of reducing friction and wear. Most of the effects noted are qualitatively self-evident, but few have been quantitatively modeled or experimentally evaluated. The model developed in this study considers only the effects of reducing wear and friction on the direct energy used to overcome friction at the tool-workpiece interface and the energy use (indirect) as embodied in worn tools.

4.2 THE GENERAL ENERGY CONSERVATION IMPACT MODEL

A flow chart for the model is shown in Figure 4.1. Two estimates contribute to the tribological sink. The first is the frictional sink: the

TABLE 4.1. Impact of Friction and Wear Reduction on Energy Use in Metalworking

Metalworking-Related Energy Use			Relevant To:		Effect of a Reduction In:	
Type	Subtype	Specific Use	Cutting	Forming	Friction	Wear
Direct	• Delivered horsepower to the workpiece during metalworking	• Deformation	x[a]	x	No	No
		• Fracture	x	x	No	No
		• Friction	x	x	Yes, Decrease	Yes, Decrease
	• Support systems, during cutting	• Coolant Pump	xxx[b]	x	No[a]	No[a]
		• Lubricant Pump	xxx	x	No[a]	No[a]
		• Workpiece Feed	xxx	x	Yes, Increase[c]	Yes, Increase[c]
		• Control Systems	xxx	x	No	No
		• Other Mechanical Systems (especially drive frictional losses)	xxx	x	No	No
Indirect	• Machine Specific	• Embodied Energy in Worn Tools	x	x	Yes, Decrease	Yes, Decrease
		• Embodied Energy in Coolants	x	x	Depends[a]	Depends
		• Embodied Energy in Lubricants	x	x	Depends[a]	Depends
		• Idling Between Cuts	xxx	x	Decrease	Decrease
		• Tool Change	x		Decrease	Decrease
		• Set Up and Gauging Workpiece Load/Unload	xx	x	No	No
	• Manufacturing System Specific	• Changes in total energy use of the production system attributable to change in metalworking parameters (speed, feed, depth of cut, etc.)	x	x	Yes, Decrease[d]	Yes, Decrease[d]
	• Economy-Specific	• Changes in total energy use of the economy at large attributable to the quality of the metal-worked product	x	x	Yes, Decrease[d]	Yes, Decrease[d]

(a) It might be argued that with reduced friction and wear at the tool-workpiece interface the energy used at their locations can be reduced also. For example, at reduced friction, the workpiece temperature is lower and there is a correspondingly lesser need for coolant and lubricant pumping. However, in practice, the lubricant and coolant levels and pumping rates are pre-set and unlikely to be changed as cutting proceeds.

(b) x = Relevant
xxx = Very relevant

(c) Because the feed rate can be increased.

(d) But very difficult to quantify.

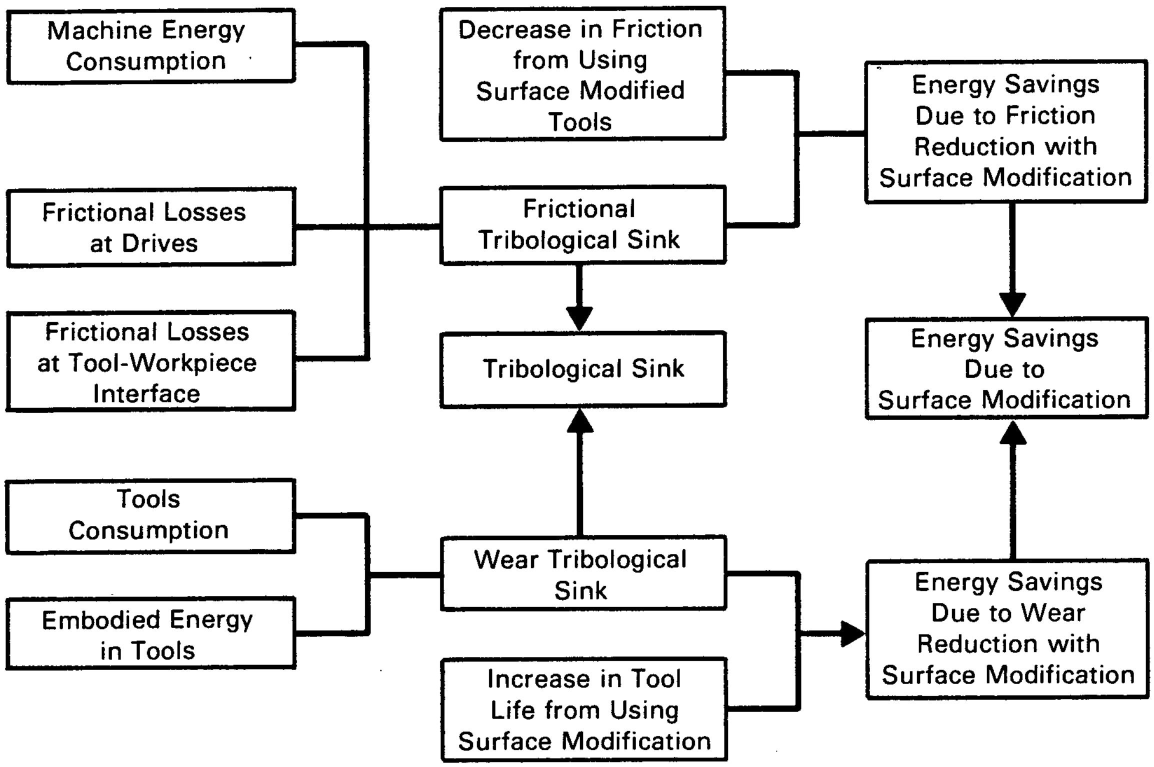


FIGURE 4.1. Energy Savings Estimation Model

sum of frictional losses at the machine drive systems and the tool-workpiece interface. The second is the wear sink: the sum of the energies embodied in the alloys used to make the worn metalworking tools. The tribological sink is the sum of the two estimates. The energy savings due to surface modification equal the tribological sink adjusted downward to take into account increased tool life and the reduction in friction.

4.2.1 Machine Energy Consumption (E)

4.2.1.1 Metalforming (E_f)

With few exceptions, industrial metalforming--especially in Industry Group 34, Fabricated Metal Products, which uses most of the U.S. metalforming machines--is a high production operation. The machines often run continuously in one, two, even three shifts and at their rated capacity. The model estimates machine energy consumption in metalforming by multiplying the rated

horsepower of the main motor drive of metalforming machines by the number of machines and the number of working hours per year. Thus:

$$E_F = \sum_{i,j} n_{i,j}\, p_i\, h \quad (\text{hp - hr})$$

where:

$n_{i,j}$ = number of machines i in industry j

h = total hours worked/year (hours)

p_i = rated horsepower of main drive motor of machine i (horsepower)

4.2.1.2 Metalcutting (E_e)

Industrial metalcutting is essentially a batch operation. Metalcutting machines do not run continuously; in fact, productive cutting time is approximately 20 percent of the total working time, as shown in Figure 4.2 (Ref. 1).

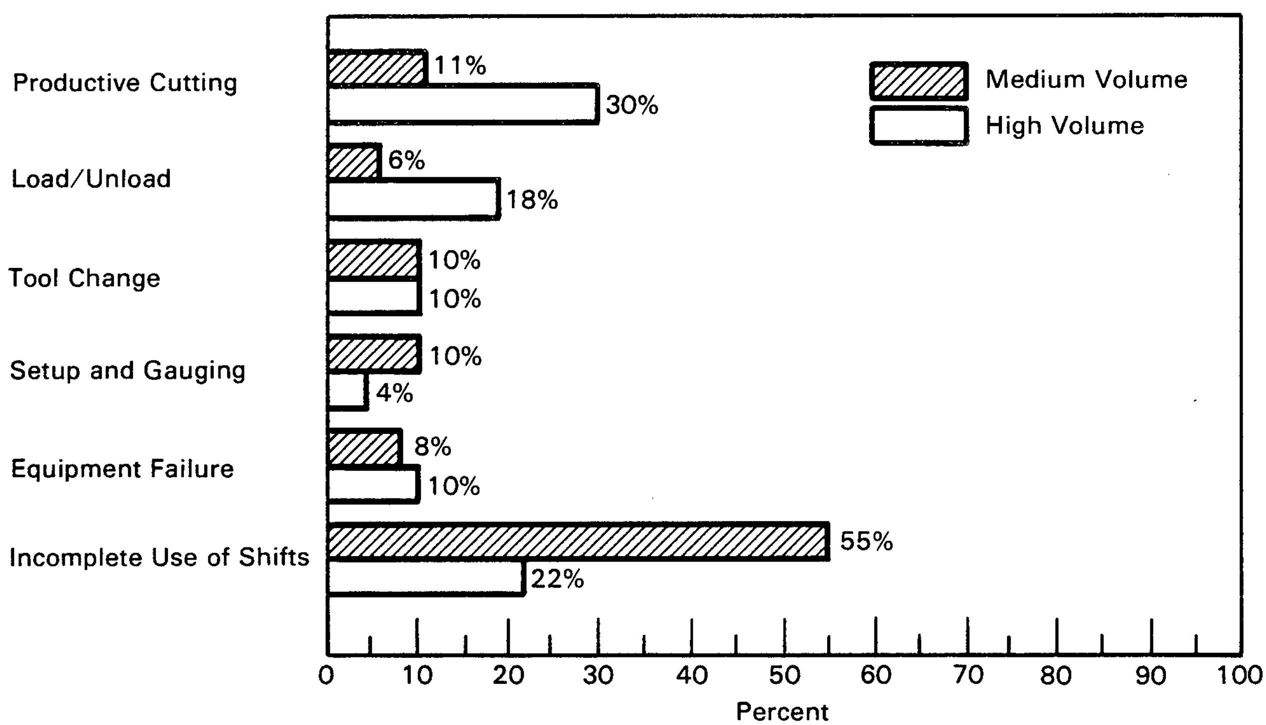


FIGURE 4.2. Machine Utilization in Metalcutting (Ref. 1)

Furthermore, metalcutting machines, whether operated manually or by computer, are run at optimum conditions for the material being cut and the type of cut to be made. Taking these considerations into account P_i (as defined above) is now written as:

$$P_i = \frac{1}{e} \sum_{i,j} P_{a,i} \frac{C_{a,i}}{\sum_a C_{a,i}} \quad \text{(hp)}$$

where:

$C_{a,j}$ = consumption of alloy a by industry j (ton/year)

$P_{a,i}$ = power required at the tool point to perform a standard operation on machine i on an alloy a (hp)

so that:

$$E_c = \sum_{i,j} n_{i,j} \left[P_{a,i} \left(\frac{C_{a,i}}{\sum_a C_{a,i}}\right)\right] \frac{h}{e} s \qquad \text{(hp - hr)}$$

where:

s = percent of the total working time spent (%)

e = efficiency of the spindle drive system (%)

The term $P_{a,i}$ is machine-, process-, and alloy-specific. Equations to compute $P_{a,i}$ from machining conditions are available from handbooks (Ref. 2,3,4). For example, for turning, milling, and drilling:

$$P_{a,turning} = 12 \times d \times fr \times V_c \times P_a^*$$

$$P_{a,milling} = w \times d \times fm = w \times d \times ft \times h \times rpm \times P_a^*$$

$$P_{a,drilling} = \frac{D^2}{4f\bar{m}} P_a^*$$

where:

d = depth of cut (inches)

fr = feed rate (inches per minute)

V_c = cutting speed (feet per minute)

$P_a{}^*$ = unit power, horsepower to remove a unit volume of material per minute (horsepower per cubic inch per minute)

w = width of cut (inches)

fm = feed rate (inches per minute)

ft = feed rate (inches per tooth)

n = number of teeth in cutter

rpm = revolutions per minute of work or cutter

D = diameter of drills (inches)

4.2.2 Frictional Losses at Drive System Z

Frictional losses at drive systems are caused by inefficiencies in converting the raw electric motor power output to useful horsepower at the tool point. Such inefficiencies arise in the spindle drive systems, which are usually transmission belts and bearings. In terms of the previously defined variables, Z is written as:

$$Z = (1 - e)\ E \qquad (\text{hp} - \text{hr})$$

Handbook data give values for (1 - e) (as a percentage of raw electric motor power output) of up to 25 percent for metalforming machines and 20 percent for metalcutting machines (Refs. 2, 3). These values for (1 - e) are assumed in this study.

4.2.3 Frictional Losses at the Tool-Workpiece Interface I

From the first principle, frictional losses at the tool point are equal to the power used to overcome friction multiplied by the metalworking time:

$$I = \sum_{I,J} n_{I,J} \left[p_i \; (1 - e) - P_{wi}\right] h \; s \qquad \text{(hp/hr)}$$

where the new variable, P_{wi}, is the power used to form or cut the metal, the term $P_{i(1 - e)}$ is the power delivered at the tool point, and the difference $(P_i(1 - e) - P_{wi})$ is the power used to overcome frictional forces. If an efficiency ratio u is now defined as the ratio of the power used to overcome friction to the power used to work the metal:

$$u = (P_i(1 - e) - P_{wi})/P_{wi}$$

I can be rewritten as:

$$I = \sum P_i \frac{(1 - e)}{(u + 1)} u \; n_{ij} \; h \; s \; s \qquad \text{(hp/hr)}$$

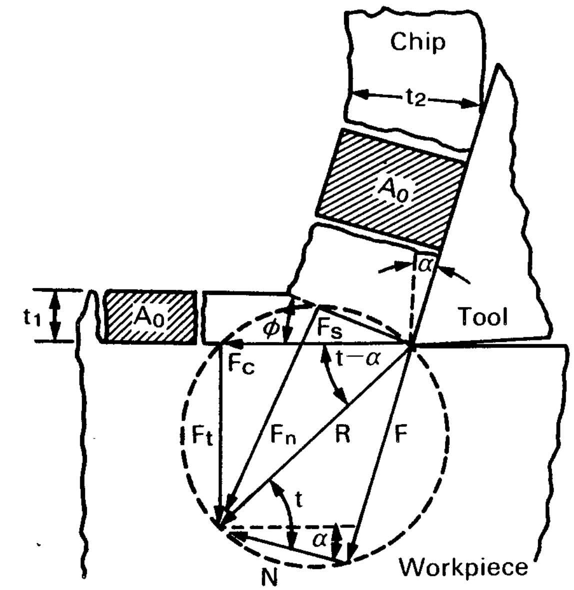
In defining u, this study assumes that all work done at the tool-workpiece interface is either frictional or metalworking (e.g., deformation, fracture, or creation of new surfaces). This assumption is also made for metalcutting; it is applicable in metalforming only when the work also includes <u>redundant work</u> which is the extra work that must be expended when a material does not deform homogeneously.

4.2.3.1 <u>The Efficiency Ratio u in Metalcutting</u>

The efficiency ratio u in metalcutting is estimated using the orthogonal cutting model. This model describes the forces at the cutting tool when its edge is perpendicular to the direction of relative work/tool motion. A summary of the orthogonal cutting model is shown in Figure 4.3. Although most metalcutting operations are oblique, i.e., with the edge of the tool not perpendicular to the direction of the work/tool motion, the orthogonal cutting model provides a good approximation of the forces and work done in metalcutting.

Using the symbols and equations defined in Figure 4.3, the metalcutting efficiency ratio u_c in metalcutting can be written as:

Quantity	Equation	
Coefficient of friction	$u = \dfrac{F_t + F_c \tan\alpha}{F_c - F_t \tan\alpha}$	(1)
Friction force	$F = F_t \cos\alpha + F_c \sin\alpha$	(2)
Mean shear strength	$S_s = \dfrac{F_c \sin\phi \cos\phi - F_t \sin^2\phi}{A_0}$	(3)
Work done in shear	$W_s = S_s [\cot\phi + \tan(\phi - \alpha)]$	(4)
Work done in overcoming friction	$W_f = \dfrac{F}{A_0} \; \dfrac{\sin\phi}{\cos(\phi - \alpha)}$	(5)
Total work done in cutting	$W_n = \dfrac{F_c}{A_0}$	(6)



where A_0 = cross-sectional area of chip before removal from workpiece, sq. in.

F = friction force; force component acting between tool face and sliding chip, lb

F_c = cutting force; force component acting in direction of tool travel, lb

F_t = thrust force; force compartment acting in direction perpendicular to surface generated, lb

S_s = mean shear stress on shear plane; mean shear strength of metal being cut, psi

W_f = work done in overcoming friction between chip and tool per unit volume of metal removed, in.-lb per cu in.

W_n = total work done in cutting per unit volume of metal removed, in.-lb per cu in.

W_s = work done in shearing of metal per unit volume of metal removed, in.-lb per cu in.

α = effective rake angle of tool as measured in a plane perpendicular to its cutting edge, deg

ϕ = shear angle; angle between shear plane and surface being generated, deg

FIGURE 4.3. The Orthogonal Cutting Model (Ref. 5)

$$u = \frac{w_f}{w_n} = \frac{\sin\phi\cos\phi - (f_t/f_c)\sin^2\phi\,(\cot\phi + \tan(\phi - \alpha))}{((f_t/f_c)\cos\alpha + \sin\alpha)((\sin\phi/\cos(\phi-\alpha))}$$

with the shear angle ϕ defined as:

$$\phi = \tan^{-1}\frac{b\cos\alpha}{1 - b\cos\alpha}$$

where the new variable b, the cutting ratio, is defined as the ratio of the chip thickness to the depth of cut.

In the above expression for u_c, only one variable, the rake angle of the tool, is known. All other variables must be determined experimentally. Selected calculated values for u_c are shown in Table 4.2 for various cutting force f_t/f_c ratios and rake angles at a cutting ratio b equal to 2. As seen, changes in the ratio u closely parallel those of f_t/f_c but are not too sensitive to changes in the rake angle.

To a first approximation, most cutting operations have an f_t/f_c ratio of about one-half (Ref. 6). Further, to achieve optimum surface finish and continuous chip formation, the cutting ratio should be high, ranging in value from 1.5 to 3.0 (Ref. 3). The most commonly used turning, drilling, and milling tools have positive rake angles that are relatively small, from 0 to 15 degrees (Refs. 2, 3, 4, 7). Thus, using an f_t/f_c ratio of 0.50, a cutting ratio b of 2, and a rake angle of 10 degrees, a calculated value for the metalworking efficiency ratio u_c is 0.5. In this model, this value for u_c is used for all metalcutting operations.

The effect of surface modified tools is usually seen as a percentage decrease in the cutting force. From the definition of u, such a percentage decrease translates directly into an equal drop in the efficiency ratio.

TABLE 4.2. Calculate Values for Cutting Efficiency u as a Function of f_t/f_c and the Rake Angle a

ft/fc	a	u
0.6	0	0.66
	5	0.61
	10	0.57
	15	0.55
0.5	0	0.6
	5	0.54
	10	0.51
	15	0.49
0.4	0	0.5
	5	0.46
	10	0.43
	15	0.41
0.3	0	0.4
	5	0.31
	10	0.31
	15	0.31

4.2.3.2 The Metalforming Efficiency Ratio u_f

Unlike metalcutting, metalforming operations cannot be described by a single mathematical model. An efficiency ratio must be assessed for each metalforming operation.

Shearing. The thickness of the sheet metal used in shearing ranges from a few hundredths of an inch to an inch. For thin sheets, friction does not have a significant effect on the shearing load force (Ref. 8). For thick sheets, force relations similar to those found in metalcutting might apply (Refs. 9, 10). Most sheet metals that are sheared are thin. Thus, for shearing, an efficiency ratio equal to zero is used.

Punching. The mathematical modeling of punching forces is difficult because the interactions among the forces are complex. Even in a simple punching operation such as the radial drawing of cups, the loading force has three components: an ideal load to deform the metal, a frictional load to overcome friction, and an ironing load to thin the cup wall. Further, each of these loads has several subloads. The ideal load consists of a radial drawing load, a load to stretch form the blank over the die radius, a load to draw the metal through the throat of the die, and a load to stretch the form over the punch radius. An exact and complete model of the punching process is not yet available, although many attempts have been made, notably by Chang and Swift (Ref. 11).

It is possible, however, to obtain a first estimate of the efficiency ratio in punching from experimental results. Following Hosford, the ratio of the redundant work to the total work in cup drawing is approximately 0.74-0.79, where redundant work is also defined to include friction (Ref. 12). Assuming that redundant work is nearly equal to frictional work, an efficiency ratio of approximately 37 percent would be derived. This figure compares with those obtained by Freeman and Leeming, who determined that the frictional component of the punch load in the ironing of thin walled metal cups is approximately 30 percent (Ref. 13), and with the generalization of Blazynski, who found that friction accounts for 10-20 percent of the force requirement in most metal-forming operations (Ref. 14). Using these results, this study assumes an efficiency ratio in punching of 30 percent.

In many punching operations, such as drawing, doubling the coefficient of friction also doubles the contribution of friction to the load force (Ref. 15). This study, therefore, assumes that the percentage decrease (or increase) in the efficiency ratio is the same as that of the coefficient of friction.

Bending and Forming. The friction component of the load force in bending operations such as rotary draw bending and roll bending is negligible because tool-workpiece contact is minimal. On the other hand, compression bending and stretch forming, as well as most tube forming operations (e.g., tube flaring,

flanging, beading, curling, expanding, reducing, and swaging), rely on frictional forces to shape the metal. In other words, a certain amount of friction is desirable in these operations (Ref. 16). Therefore, this study does not consider bending and forming machines.

Forging and Pressing. Under slipping friction conditions, the forging pressure is given by (Ref. 16):

$$P = \sigma_o \exp[(\frac{2\mu}{h}) (a \pm x)]$$

while the forging pressure if friction is not present is simply the yield stress of the material:

$$P_{ideal} = \sigma_o$$

In these equations, the symbols are:

- μ = coefficient of friction between the die and the workpiece
- a = half width of the workpiece (mm)
- h = height of the workpiece (mm)
- x = position along the x-axis; x = 0 is at the vertical centerline

The forging pressure is maximum at the center when x = 0 and is minimum at the edges when x = a. To simplify the calculation, a mean pressure (P_{mean}) can be used, where:

$$P_{mean} = \sigma_o (1 + \frac{\mu a}{h})$$

since it is true that: $(2 \frac{u}{h} (a \pm x) \approx 1 + 2 \frac{u}{h} (a \pm x))$

when $2 \frac{u}{h} (a \pm x)$ is less than 1, which is always true.

The efficiency ratio in forging can be written as:

$$u = \frac{P_{mean} - P_{ideal}}{P_{ideal}} = \mu \frac{h}{a}$$

This study uses the simple case where a = h, so that the efficiency ratio is equal to the coefficient of friction.

Other Forming Operations. Rolling has been considered by PNL as part of its study on tribological sinks in the primary metals industries. This study, therefore, does not include rolling even though it is probably the most common metal processing operation (most metals are usually cast and rolled after refining).

Wire drawing machines make up only 2 percent of all metalforming machines. They can be omitted without unduly affecting the results of the study.

Extrusion is a specialized pressing operation. In effect, in extrusion, a metal cylinder is forced through a die orifice by means of a ram (direct extrusion), or a hollow ram is forced into the metal cylinder so that metal flows through the die and into the ram (indirect extrusion). Extrusion machines are implicitly included in the presses and forges group in this study, and the same functional relation between the coefficient of friction and the efficiency ratio is used to model extrusion. Such a procedure is justifiable because it can be shown that the efficiency ratio in extrusion is proportional to the coefficient of friction in the same manner as that found for forging. Specifically, in extrusion:

$$u = \frac{2L}{d_1}$$

where:

L = length of the cylinder

d_1 = original diameter of the cylinder.

4.2.4 Other Components of the Model

The friction tribological sink T_f is:

$$T_f = I + E$$

The wear tribological sink T_w is:

$$T_w = \sum_{a,j} a_a \, m_{a,j}$$

where:

q_a = embodied energy of alloy a

$m_{a,j}$ = consumption of tool alloy a in industry j (ton/year).

The tribological sink E_s in metalworking is:

$$E_s = T_f + T_w$$

The energy savings due to friction reduction (I_f) from using surface modification technologies is:

$$\Delta I = I(u_2) - I(u_1)$$

$$= \sum_{i,j} n_{i,j} \, p_i \, h \, s \left(\frac{1 - e}{1 + u_2}\right) u_2 - \sum_{i,j} n_{i,j} \, p_i \, h \, s \left(\frac{1 - e}{1 - u_1}\right) u_1$$

$$= \sum_{i,j} n_{i,j} \, p_i \, h \, s \, (1 - e) \frac{(u_2 - u_1)}{(u_2 + 1)\,(u_1 + 1)}$$

where u_2 and u_1 are the efficiency ratios both before and after the introduction of surface modified tools.

The energy savings due to wear reduction from using surface modification technologies, T_w, are:

$$\Delta T_w = \sum_{a,j} a_a \, m_{a,j} \left(\frac{v}{v+1}\right)$$

where Δ is the average increase in tool life (in percent) attributable to the use of surface modified tools.

The energy savings due to the use of surface modification technologies in metalworking are:

$$\Delta E_{sm} = \Delta I_f + \Delta I_w$$

4.3 DATA USED IN THE MODEL

The following data are needed to implement the model: the number of machine tools used in the United States, rated horsepower of the main motor of machine tools, friction coefficients with and without surface modified tools in metalworking, efficiency of spindle drive, and consumption of alloys in the metalworking industries.

4.3.1 The Machine Tool Data

The 13th American Machinist Inventory of Metalworking Equipment 1983 is the primary source for the number of machine tools in the United States (see Section 3.2). This section concentrates on how the data are used in this model.

4.3.1.1 Metalcutting Machines Included in the Study

Metalcutting machines are classified according to the machining operation involved: turning, milling, broaching, and cutoff and sawing. In the turning machine group are numerically controlled (NC) turning machines, non-numerically controlled (Non-NC) turning machines, NC and Non-NC boring machines, and machining centers, which are essentially multipurpose machines that can turn, bore, drill, or mill. The milling group includes NC and Non-NC milling machines and gear cutting and finishing machines, which are basically specialized milling devices. The drilling group includes NC and Non-NC drilling machines and tapping machines. The broaching groups include broaching machines

of all types. The cutoff and sawing group includes hacksaw, circular cutoff sawing, bandsaws, contour sawing and filing, and all other cutting machines except those using abrasive wheels. Table 4.3 gives the type and number of metalcutting machines considered in this study.

4.3.1.2 Metalforming Machines Included in the Study

Metalforming machines are classified in three major groups: punching and shearing, bending and forming, and presses and forges. The punching and shearing group includes all NC and Non-NC punching and shearing machines. The bending and forming group includes NC and Non-NC bending machines such as press brakes (mechanical or hydraulic), bending rolls, rotary bending and forming, and ram and press bending machines. The press and forges group includes all mechanical, hydraulic, or pneumatic presses and forging machines such as headers and upsetters, swaging machines and expanders, and forging presses. Table 4.4 lists the types and number of the machines considered in this study.

4.3.2 The Main Spindle Drive Horsepower Rating

DHR, Inc., compiled data on the horsepower rating of the main spindle drive of machine tools by surveying existing equipment. The primary data sources were the manufacturers' product specification sheets. The manufacturers were contacted by mail, by telephone, and directly at the International Machine Tool Show (IMTS) held in Chicago early in September, 1984.

Spindle drive horsepower data are important and useful as upper bound checks on the calculated horsepower requirements in metalcutting and as the raw or primary data for estimating energy consumption by metalforming machines. For these machines, the weighted average horsepower of the main drive motor was calculated using the number of machines as the weighting factor. Appendix C gives the spindle drive horsepower of the metalworking machines surveyed. Table 4.5 gives the calculated horsepower for the metalcutting machines considered in this study, and Table 4.6 gives their materials averaged horsepower.

4.3.3 Coefficient of Friction Data for Metalforming Machines

Metalworking machines are usually operated only under lubrication. The coefficient of friction under lubricated conditions can vary widely from one

TABLE 4.3. Metalcutting Machine Tools Considered in this Study

Machine Type	Industry Group (1)								
	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
1. TURNING MACHINE GROUP	982	20904	85327	191914	42330	59868	24123	8834	435208
- NC Turning Machines	46	842	4348	18592	2677	4922	1538	387	33352
- Non-NC Turning Machines	811	17390	75235	136490	34652	39818	20362	7569	332327
- NC Boring Machines	25	271	500	2935	182	907	106	138	5064
- Non-NC Boring Machines	74	2087	3592	19980	3065	10094	877	693	40462
- Machining Centers	26	350	1652	13917	2644	4127	1240	47	24003
2. DRILLING MACHINE GROUP	2606	18528	68675	125146	44179	40497	21686	7971	329288
- NC Drilling Machines	58	261	1121	4205	1150	718	227	253	7993
- Non-NC Drilling Machines	2271	14873	54602	109924	37116	36191	19200	7276	281453
- Tapping Machines	257	2620	8085	7989	5121	2007	1669	391	28139
- Threading Machines	20	774	4867	3028	792	1581	590	51	11703
3. DRILLING MACHINE GROUP	1181	9610	39471	128121	27206	42089	15317	6247	269242
- NC Milling Machines	45	433	1676	7876	1983	2145	1132	639	15929
- Non-NC Milling Machines	1099	8658	36102	103072	23862	27199	12907	5580	218479
- Gear Cutting Machines	37	519	1693	17173	1361	12745	1278	28	34834
4. BROACHING MACHINE GROUP	33	652	2624	6825	821	5197	233	120	16505
5. SAWING MACHINE GROUP	2259	10458	40115	56807	18911	21371	8587	6999	169107

(1) SIC Codes:

25: Furniture and Fixtures
33: Primary Metal Industries
34: Fabricated Metal Products
35: Machinery, Except Electrical
36: Electric and Electronic Equipment
37: Transportation Equipment
38: Instruments and Related Products
39: Miscellaneous Manufacturing Industries

TABLE 4.4. Metalforming Machine Tools Considered in this Study

Machine Type	Industry Group (1)								
	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
1. PUNCHING AND SHEARING GROUP	1854	2924	26139	19571	9565	7222	3296	2015	72586
- NC Punching and Shearing	166	95	2490	1290	1013	373	368	428	6223
- Non-NC Punching and Shearing	1688	2829	23649	18281	8552	6849	2928	1587	66363
2. BENDING AND FORMING GROUP	4487	3177	30196	19945	8432	9591	2569	1473	79870
- NC Bending and Forming	197	145	989	493	247	428	71	15	2585
- Non-NC Bending and Forming	4290	3032	29207	19452	8185	9163	2498	1458	77285
3. PRESSES AND FORGES GROUP	9040	16380	114356	46479	45114	32316	11570	14279	289534
- Mechanical Presses	8508	7187	89051	29289	29544	19010	6376	10008	198973
- Hydraulic Presses	283	6422	10494	13300	9131	9712	2530	1420	53292
- Pneumatic Presses	159	567	3512	2309	5592	1557	2563	1397	17656
- Forges	90	2204	11299	1581	847	2037	101	1454	19613

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TABLE 4.5. Cutting Conditions and Derived Motor Horsepower

MATERIALS & PROCESS	TOOL MATERIAL	DEPTH d (in)	FEED fr (ipr)	FEED fm (ipm)	FEED ft (ipt)	SPEED Vc (fpm)	METAL REMOVAL RATE Q (in3/min)	UNIT POWER P (hp)	REQUIRED SPINDLE HPs POWER (HP)	REQUIRED MOTOR HPm POWER (HP)
1. TURNING										
-Carbon steels	HSS	0.25	0.02	n.a	n.a	120	7.20	1.50	10.80	13.50
-Alloy steels	HSS	0.25	0.02	n.a	n.a	100	6.00	1.30	7.80	9.75
-Al & Al alloys	HSS	0.25	0.03	n.a	n.a	800	72.00	0.25	18.00	22.50
-Cu & Cu alloys	HSS	0.25	0.02	n.a	n.a	300	18.00	1.00	18.00	22.50
2. FACE MILLING (milling width: 5 in.; 10 teeth cutter; mill cutter dia.= 5in)										
-Carbon steels	HSS	0.15	n.a	n.a	0.012	200	3.60	1.40	5.04	6.30
-Alloy steels	HSS	0.15	n.a	n.a	0.007	175	1.84	1.40	2.57	3.22
-Al & Al alloys	HSS	0.15	n.a	n.a	0.01	250	3.75	0.32	1.20	1.50
-Cu & Cu alloys	HSS	0.15	n.a	n.a	0.01	250	3.75	1.00	3.75	4.69
3. DRILLING (1/2 in. diameter drill)										
-Carbon steels	HSS	n.a	0.01	n.a	n.a	80	2.40	1.30	3.12	3.90
-Alloy steels	HSS	n.a	0.002	n.a	n.a	45	0.27	1.50	0.41	0.51
-Al & Al alloys	HSS	n.a	0.012	n.a	n.a	200	7.20	0.20	1.44	1.80
-Cu & Cu alloys	HSS	n.a	0.01	n.a	n.a	140	4.20	0.80	3.36	4.20
4. BROACHING (8 tooth broach; width of cut W = 1 in.)										
-Carbon steels	HSS	0.04	n.a	n.a	0.005	40	19.20	0.50	9.60	12.00
-Alloy steels	HSS	0.032	n.a	n.a	0.004	30	11.52	1.00	11.52	14.40
-Al & Al alloys	HSS	0.048	n.a	n.a	0.006	40	23.04	0.20	4.61	5.76
-Cu & Cu alloys	HSS	0.04	n.a	n.a	0.005	25	12.00	0.40	4.80	6.00

NOTES: A) Metal removal rate and horsepower equations:

- Turning : Q = 12 x d x fr x Vc
- Milling : Q = w x d x fm = w x d x ft x n x rpm = w x d x ft x n x 3.82
- Drilling : Q = 3.1416 x D x fr x 3.82 x Vc / 4
- broaching : Q = 12 x Vc x ft x n = 12 x Vc x dt
- Required power: HPs = Q x P (at spindle)
- Required power: HPm = Q x P / E (at motor)
- Drilling rpm : 3.82 x Vc / D

where: Q = metal removal rate, cubic inches per minute
d = depth of cut, inches
dt = total stock removed per stroke, inch. For Broaching, dt = chip load
fr = feed, inches per revolution
Vc = cutting speed, feet per minute
W = width of cut, inches
fm = feed rate, inches per minute. For drilling, fm = fr x rpm = fr x 3.8
ft = feed rate, inches per tooth
n = number of teeth in cutter
rpm = revolution per minute of work or cutter
D = diameter of drill or milling cutter, inches
HPs = required horsepower at spindle, hp
HPm = required horsepower at motor, hp
E = efficiency of spindle drive, about 80%
P = unit power, horsepower per cubic inch per minute

B) HSS = high speed steel

machine to another and from location to location at the tool-workpiece interface. For example, the coefficient of friction in rolling is maximum near the center of the contact zone.

Coefficient of friction data for many metalforming machine and lubrication conditions have been compiled by Schey (Ref. 6). They are given in Table 4.7. In this study, the arithmetic average of these values is used.

TABLE 4.6. Materials Averaged Motor Horsepower, by Operation and Industry

PROCESS	MATERIALS AVERAGED MOTOR HORSEPOWER BY INDUSTRY (hp)[1]							
	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39
1. Turning	14.20	22.50	13.95	14.08	15.04	13.89	13.02	10.02
2. Drilling	3.64	3.34	3.54	3.35	3.50	3.51	1.81	0.76
3. Milling	5.79	3.55	5.76	5.51	5.47	5.75	3.97	3.44
4. Broaching	11.56	5.91	11.68	11.58	10.95	11.72	12.24	14.22

(1) SIC Codes:

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36: Electric and Electronic Equipment

37: Transportation Equipment

38: Instruments and Related Products

39: Miscellaneous Manufacturing Industries

The effects of surface modification technologies on the coefficient of friction were discussed in Section 4.3.3.

4.4 METALWORKING ALLOY CONSUMPTION DATA

The U.S. Bureau of the Census provides data on the consumption of major engineering alloys in the 1977 Census of Manufacturers (Ref. 17). For this study data on the consumption of carbon steels, alloy steels, copper and copper alloys, and aluminum and aluminum alloys were needed. Such data expressed as a percentage of the total tonnage consumed in each industry group are shown in Tables 4.8 and 4.9.

The metalforming and metalcutting tool manufacturers are SIC 35441 and SIC 35451, respectively. Data on the tonnage of alloys used by these industries are not available, but estimates can be made using Census Bureau data on values

TABLE 4.7. Typical Metalworking Coefficients

Material	Pressworking[a]	μ	Hot Forging Lubricant[a]	μ	Cold Forging/Extrusion Lubricant[b]	μ
Steels	Dry (pickle oil)	0.2	None	ST	Soap solution	0.2
	Soap solution	0.15	Salt solution (on die)	0.4	EM (M.O. + fat)	0.2
	EM (M.O. + fat)(+E.P.)	MF	Soap (on die)	0.3	EM (M.O. + fat + E.P.)	0.2
	M.O. + fat (+E.P.)	MF	GR in water (on die)	0.2	M.O. (20-800) + fat + E.P.	0.15
	Fat (tallow)	0.07	GR with binder (on die)	0.2	Compounded M.O. + GR or MoS_2	0.15
	Soap (water-soluble) film	0.05			Sulfonated fatty oil	0.1
	Wax (chlorinated)	0.05			Lime + compounded oil	0.1
	MoS_2 or GR in grease	0.05			Copper + compounded oil	0.1
	Polymer coating (+MoS_2)	0.05			Phosphate + soap	0.05
	Phosphate + soap	0.05			Phosphate + soap + MoS_2	0.05
	Metal (Sn) + EM	0.05				
Stainless Steels and Ni Alloys	EM (M.O. + Cl)(or fat)	0.2	GR in water (on die)	0.2	M.O. (20-800) + Cl additive	0.2
	M.O. + Cl additive	MF	Glass (10-100 Pa·s) + GR (on die)	0.05	Lime + compounded oil	0.15
	Chlorinated wax	0.07			Copper + compounded oil	0.1
	Polymer coating	0.07			Polymer coat	0.05
	Oxalate + soap	0.07			Oxalate + soap	0.05
	Metal (Cu) + M.O.	0.05				
Al and Mg Alloys	EM (M.O. + fatty derivatives)	0.15	Soap (on die)	ST	M.O. (10-100) + fatty derivatives	0.15
	M.O. + fatty derivatives	MF	GR in water (on die)	0.3	Lanolin; dry soap film	0.07
	Soap or wax (lanolin) coating	0.05	GR with binder (on die)	0.2	Phosphate + soap	0.05
	Polymer coating	0.05				
	Warm: GR film	0.1				
Cu and Cu Alloys	Soap solution	0.1	Soap (on die)	0.3	Soap solution	0.1
	EM (M.O. + fat)(or fat)	0.1	GR in water (on die)	0.15	EM (M.O. + fat)	0.1
	Drawing paste (EM of fat)	0.1			EM (fat)	0.1
	Fat (tallow)	0.07			M.O. (20-400) + fat (+Cl additive)	0.1
	Pigmented tallow (MoS_2, etc.)	0.05			Fat; wax (lanolin)	0.07
					Soap (Zn-stearate)	0.05
					GR or MoS_2 in grease	0.07

Notes: ST = Sticking friction
EM = Emulsion
M.O. = Mineral oil
GR = Graphite
EP = Additive (S, Cl, P, also sulfochlorinated fats)
MF = Mixed film lubrication; μ = 0.05 - 0.15

TABLE 4.8. Alloy Consumption by Metalworking Industries, 1977

	Materials Consumed	Cut	Form	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	Total
1	Steel Mill Shapes and Forms											
1.1	Carbon Steel											
	- Bars and shapes except concrete reinforcing bars	Y	Y	15.3		4098	2428.2	451.2	1944.7	23	1.8	8962.2
	- Sheet and strip	Y	Y	1714.3		18614.7	3448	4242.3	9401.1	95.4	6.7	37522.5
	- Plates	Y	Y	3.8		3350.7	3102.2	121.4	2231.2	6.3		8815.6
	- Structural shapes	Y	Y	17.9		3020.1	1030.4	139.1	773.2			4980.7
	- Wire and wire products	Y	Y	15.8		1949.2	210.5	362	212.4	6		2755.9
	- All other mill shapes and forms	Y	Y	479.2		9426.6	1221.4	805.7	811.4	44	446.3	13234.6
1.2	Alloy Steel											
	- Bar and bar shapes except stainless	Y	Y	29		1274.5	786.1	12	852			2953.6
	- All other mill shapes and forms except stainless	Y	Y			1240.9	720.4	445.8	391.1	271	71.3	3140.5
	- Stainless steel	Y	Y									0
	- Sheet and strip	Y	Y			335.1	137.7	59.9	158.3	29.1	18.8	738.9
	- All other stainless steel mill shapes and forms	Y	Y	24.4		243.2	148.8	28.2	52	13.2	17.4	527.2
2	Copper and Copper-Base Alloy Mill Shapes and Forms											
2.1	Brass Wire for Electrical Conduction	L	Y		329	4	18.4	102.3	27	6.2	0	486.9
2.2	Insulated Wire and Cable (copper content)	L	Y		33.5	3.2	65.9	227.3	99.3	4.2		433.4
2.3	Brass Mill Shapes											
	- Rod, bar and mechanical wire	Y	Y		0	476.4	91.6	220.2	183	27.5		990.7
	- Plate, sheet, and strip	Y	Y		55.9	204.9	168.6	162.8	165.9			758.1
	- Pipe and tube	Y	Y		0	152.5	232.8	44.6	35.2		0	465.1
3	Aluminum and Aluminum-Base Alloy Mill Shapes and Forms											
3.1	Sheet, Plate and Foil	Y	Y	30.4	0	3313.7	372.1	246.2	638.7		4.1	4605.2
3.2	Extruded Shapes	Y	Y	98.3	0	735.2	162.2	146.9	312.1		17.3	1472
3.3	All Other Aluminum Mill Shapes and Forms	Y	Y	79.8	62	661.7	175.5	178	43.2		51.3	1251.5
4	Selected Castings and Forgings											
4.1	Castings--Rough and Semifinished	Y	Y									
	- Iron--grey and malleable	Y	Y			686.5	2580.6	209.1	5008.5	0	0	8484.7
	- Steel	Y	Y			232.5	494.7	22.7	649	20.5	0	1419.4
	- Aluminum and aluminum base alloy	Y	Y			145.8	650.6	326.7	750.6	40.5	0	1914.2
	- Copper and copper-base alloy	Y	Y			114	89.3	31.5	12.4	13.4		260.6
4.2	Forgings											
	- Iron and steel	L	Y			179.2	947.8	8	1695.3	0	0	2830.3
	- Aluminum and aluminum-base	L	Y			8.8	0	0	174	0	0	182.8
	- Metal powder	L	Y									0
5	Pig Iron and Nonferrous Refinery Shapes	N	N									
5.1	Pig Iron	N	N		7257.6	77	80.8	0	48.5			7463.9
5.2	Nonferrous Refinery Shapes	N	N									
	- Copper and copper-base alloy	N	N		1907.8	68.9	25.3	11.6	0			2013.6
	- Zinc and zinc-base alloy	N	N		686.6	153	0	17.8	0			857.4
	- Aluminum and aluminum-base alloy	N	N		5565.4	247			110.5			5922.9

Legend: Y = Yes; N = No; L = Little

TABLE 4.9. Industrial Metalworking of Major Alloys, by Percentage, 1977

Materials and Processing	SIC 25 (%)	SIC 33 (%)	SIC 34 (%)	SIC 35 (%)	SIC 36 (%)	SIC 37 (%)	SIC 38 (%)	SIC 39 (%)
1. Carbon Steels								
Cutting	88.42	0.0	82.67	74.63	72.39	83.07	22.79	7.33
Forming	87.09	0.0	76.45	75.03	67.71	81.30	22.39	4.50
2. Alloy Steels								
Cutting	2.67	0.0	8.67	13.34	7.45	8.92	58.21	92.67
Forming	2.63	0.0	7.97	12.49	6.96	8.04	57.18	56.97
3. Copper and Copper Alloys								
Cutting	0.0	64.33	4.64	6.27	11.62	3.31	11.93	0.0
Forming	0.0	88.44	3.92	5.06	14.34	3.33	13.50	0.0
4. Aluminum and Aluminum Alloys								
Cutting	8.91	35.67	4.02	5.76	8.54	4.69	7.06	0.0
Forming	10.28	11.56	11.66	7.42	10.99	7.33	6.94	38.53
Total Cutting:	1	1	1	1	1	1	1	1
Total Forming:	1	1	1	1	1	1	1	1

Source: (Ref. 17)

of product shipments and the tonnage of alloys consumed by the next larger industry classifications, SIC 3544 (Special Dies, Tool, Jig, and Fixtures) and SIC 3545 (Machine Tool Accessories). The estimating procedure assumes that the ratio of the tonnage of the alloys consumed by SIC 35441 (or SIC 35451) to that consumed by SIC 3544 (or SIC 3545) is equal to the ratio of their product shipment values. The estimates obtained are shown in Tables 4.10 and 4.11. The figures probably underestimate actual consumption in view of the fact that they do not consider companies which manufacture their own forming tools.

TABLE 4.10. Shipment Values of Metalforming Accessories[1] ($ million)

Year	All Accessories a	Working Tools b	Ratio b/a (%)	Annual Growth Rate of b (%)
(A) Metalforming				
1982	N/A	N/A		
1981	6975.2	4248.5	60.91	17.47
1980	6165.3	3616.7	58.66	1.16
1979	5732.6	3575.2	62.37	18.72
1978	5058.8	3011.5	59.53	16.82
1977	4450.2	2578.0	57.93	
Average Percentage:			59.88	13.54
(B) Metalcutting				
1982[2]	3033.6	1744.2	57.50	-21.29
1981	3854.0	2352.5	61.04	9.14
1980	3531.1	2199.4	62.29	10.16
1979	3205.4	2023.6	63.13	19.76
1978	2676.6	1651.7	61.71	19.55
1977	2238.9	1376.4	61.48	
Average Percentage:			61.19	9.33

(1) Ref. 18.
(2) Ref. 19.

TABLE 4.11. Estimated Alloy Consumption for Metalworking Tools (1000 tons)

Alloy	1977[a] All Forming Accessories	1977[a] Forming Dies[b]	1983[c] Forming Dies	1977[a] All Cutting Accessories	1977[a] Cutting Tools[d]	1983[e] Cutting Tools
Total	212.50	127.25	272.61	92.60	56.66	121.39
Carbon Steel	167.00	100.00	214.24	43.20	26.43	56.63
Alloy Steel	42.30	25.33	54.26	48.70	29.80	63.84
Stainless Steel	3.20	1.92	4.11	0.70	0.43	0.92

(a) Ref. 17.
(b) Calculated as 59.88% of all forming accessories.
(c) Calculated using an annual growth rate of 13.54%.
(d) Calculated as 61.19% of all cutting accessories.
(e) Calculated using an annual growth rate of 9.33%.

REFERENCES

1. Lyle, C. S. 1984. "A Proven Tooling System for Flexible Turning Machines." Paper presented at the 2nd Biennial International Machine Tool Technical Conference, September 5-13, 1984, Chicago, Illinois.

2. Machinability Data Center. 1980. Machining Data Handbook, Vol. 2. Netcut Research Associates, Inc., Cincinnati, Ohio.

3. Drozda, T. J., ed. 1983. Tool and Manufacturing Engineers Handbook--Volume 1: Machining. 4th Edition. Society of Manufacturing Engineers, Dearborn, Michigan.

4. Wilson, F. W., ed. 1959. Tool Engineers Handbook. 2nd ed. McGraw Hill, New York.

5. Donalson, C. et al. 1972. Tool Design. 3rd ed. McGraw Hill, New York.

6. Schey, J. A. 1983. Tribology in Metalworking, Friction, Lubrication and Wear. American Society for Metals, Metals Park, Ohio.

7. American Society of Metals. 1976. Metals Handbook--Volume 3: Machining. American Society for Metals, Metals Park, Ohio.

8. Schey, J. A., ed. 1972. Metal Deformation Processes, Friction and Lubrication. 2nd ed. Marcel Dekker, Inc., New York.

9. Rowe, G. W. 1967. Lubrication and Lubricant, ed. E. R. Braithwaite. Elsener Publishing Company, Amsterdam, New York.

10. Chang, A. and H. Swift. 1951. Proc. Inst. Mech. Engr. 165(1951):199.

11. Hosford, W. F. 1978. "Effect of Anisotropy and Work Hardening on Cup Drawing, Redrawing, and Ironing," in Formability Analysis, Modeling and Experimentation. Metallurgical Society of the AIME, New York.

12. Freeman, R. and W. Leeming. 1983. "Ironing of Thin Walled Metal Cup: The Distribution of Punch Load," BISRA Report No. MW/E/53 (1953), cited by Hosford, W. F., in Metalforming: Mechanics and Metallurgy. Prentice Hall Publishers, Englewood Cliffs, New Jersey.

13. Blazynski, T. Z. 1976. Metalforming Tool Profiles and Flow. J. Wiley and Son, New York.

14. Rowe, G. W. 1978. Principles of Industrial Metalworking Processes. Edward Arnold Publishing, London, England.

15. Kervitch, R. J. and R. K. Springborn. 1966. Cold Bending and Forming of Tubes and Other Sections. American Society of Tools and Manufacturing Engineers, Dearborn, Michigan.

16. Harris, J. B. 1983. Mechanical Working of Metal: Theory and Practice. Pergamon Press, Oxford, New York.

17. U.S. Bureau of 1978. 1977 Census of Manufacturers. Government Printing Office, Washington, D.C.

18. U.S. Bureau of the Census. 1980-81 Annual Survey of Manufacturers. Government Printing Office, Washington, D.C.

19. U.S. Bureau of the Census. July 1984. 1982 Census of Manufacturers: Preliminary Report, Industry Series. M082-I-3504(P), Government Printing Office, Washington, D.C.

5.0 RESULTS

Estimates of the tribological sinks and the energy savings achievable using surface modified tools in metalworking are presented in this section.

5.1 EFFECTS OF SURFACE MODIFICATION TECHNOLOGIES IN METALCUTTING

5.1.1 The Frictional Sink in Metalcutting

Frictional losses in metalcutting machines occur in spindle drive systems whenever a machine is running and at the tool point (i.e., the tool-workpiece interface) during productive cutting. This study estimates that frictional losses in all U.S. metalcutting machines during productive cutting only amount to 5,810 billion Btu/year, 2,490 at the drive system and 3,320 at the tool point. Table 5.1 details the assumptions and calculations for these figures.

The origins of frictional losses by machine type and industry are shown in Figure 5.1 for those at the spindle drive and in Figure 5.2 for the tool point. Turning machines account for more than one-half of both types of frictional losses in all industries. Industry Group SIC 35, Machinery Except Electrical, is responsible for nearly one-half of all losses, or 1,980 billion Btu/year.

5.1.2 The Wear Sink in Metalcutting

In Section 4.4 it was estimated that approximately 121,000 tons of steel were used as raw materials for the manufacture of small cutting tools in 1983. Using 19.2 million Btu/ton as the embodied energy in steels that are made from scrap in electric furnaces and are continuously cast, the wear sink is 2,323.2 billion Btu/year.

5.1.3 Energy Savings Achievable from Friction Reduction with Surface Modification Technologies

Assuming that surface modified tools can lower the efficiency ratio by 30 percent, as discussed in Section 2.2.4, approximately 739 billion Btu/year would result from full-scale use of these tools in metalcutting. Nearly one-half of the savings would be realized in the turning machines groups, e.g., turning and boring machines and machining centers. From an industry

TABLE 5.1. Metalcutting Energy Savings Model Inputs and Results

INDUSTRY:	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
A) MODEL INPUTS									
1. TURNING (number of machines):	982	20940	85327	191914	43220	59868	24123	8834	435208
Material-averaged motor horsepower (hp):	14.20	22.50	13.95	14.08	15.04	13.89	13.02	10.02	
losses at drive system, e (percent):	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Efficiency ratio ul:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Average working time, h (hours/year):	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	
Productive cutting time, s (percent):	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
2. DRILLING (number of machines)	2606	18528	68675	125146	44179	40497	21686	7971	329288
Material-averaged motor horsepower (hp):	3.64	3.34	3.54	3.35	3.50	3.51	1.81	0.76	
losses at drive system, e (percent):	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Efficiency ratio ul:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Average working time, h (hours/year):	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	
Productive cutting time, s (percent):	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
3. MILLING (number of machines):	1181	9610	39471	128121	27206	42089	15317	6247	269242
Material-averaged motor horsepower (hp):	5.79	3.55	5.76	5.51	5.47	5.75	3.97	3.44	
losses at drive system, e (percent):	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Efficiency ratio ul:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Average working time, h (hours/year):	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	
Productive cutting time, s (percent):	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
4. BROACHING (number of machines):	33	652	2624	6825	821	5197	233	120	16505
Material-averaged motor horsepower (hp):	11.56	5.91	11.68	11.58	10.95	11.72	12.24	14.22	
losses at drive system, e (percent):	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Efficiency ratio ul:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Average working time, h (hours/year):	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	
Productive cutting time, s (percent):	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
5. SAWING (number of machines):	2259	10458	40115	56807	18911	21371	8587	6999	165507
Material-averaged motor horsepower (hp):	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
losses at drive system, e (percent):	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
Efficiency ratio ul:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Average working time, h (hours/year):	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	2000.00	
Productive cutting time, s (percent):	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
RATIO U2/U1:	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	

SIC Codes:

25: Furniture and Fixtures
33: Primary Metal Industries
34: Fabricated Metal Products
35: Machinery, Except Electrical
36: Electric and Electronic Equipment
37: Transportation Equipment
38: Instruments and Related Products
39: Miscellaneous Manufacturing Industries

TABLE 5.1. (contd)

INDUSTRY:	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
B) RESULTS									
1. FRICTIONAL SINK AT MOTOR DRIVE SYSTEM									
1.1. ALL MACHINE GROUPS									
hp-hr/year:	4.19E+06	6.23E+07	1.89E+08	4.19E+08	1.06E+08	1.38E+08	4.60E+07	1.53E+07	9.80E+08
in kWh/year:	3.13E+06	4.65E+07	1.41E+08	3.12E+08	7.88E+07	1.03E+08	3.43E+07	1.14E+07	7.31E+08
in billion Btu/year:	1.07E+01	1.59E+02	4.81E+02	1.07E+03	2.69E+02	3.52E+02	1.17E+02	3.89E+01	2.49E+03
1.2. TURNING MACHINE GROUP									
-per machine, in hp-hr/year:	1.42E+03	2.25E+03	1.40E+03	1.41E+03	1.50E+03	1.39E+03	1.30E+03	1.00E+03	
in kWh-year:	1.06E+03	1.68E+03	1.04E+03	1.05E+03	1.12E+03	1.04E+03	9.71E+02	7.48E+02	
in million Btu/year:	3.61E+00	5.72E+00	3.55E+00	3.58E+00	3.83E+00	3.53E+00	3.31E+00	2.55E+00	
-all machines, in hp-hr/year:	1.39E+06	4.71E+07	1.19E+08	2.70E+08	6.50E+07	8.31E+07	3.14E+07	8.86E+06	6.26E+08
in kWh-year:	1.04E+06	3.51E+07	8.88E+07	2.02E+08	4.85E+07	6.20E+07	2.34E+07	6.60E+06	4.67E+08
in million Btu/year:	3.55E+03	1.20E+05	3.03E+05	6.88E+05	1.65E+05	2.12E+05	7.99E+04	2.25E+04	1.59E+06
1.3. DRILLING MACHINE GROUP									
-per machine, in hp-hr/year:	3.64E+02	3.34E+02	3.54E+02	3.35E+02	3.50E+02	3.51E+02	1.81E+02	7.55E+01	
in kWh-year:	2.71E+02	2.49E+02	2.64E+02	2.49E+02	2.61E+02	2.62E+02	1.35E+02	5.63E+01	
in million Btu/year:	9.26E-01	8.51E-01	9.00E-01	8.51E-01	8.91E-01	8.93E-01	4.61E-01	1.92E-01	
-all machines, in hp-hr/year:	9.48E+05	6.20E+06	2.43E+07	4.19E+07	1.55E+07	1.42E+07	3.93E+06	6.02E+05	1.08E+08
in kWh-year:	7.07E+05	4.62E+06	1.81E+07	3.12E+07	1.15E+07	1.06E+07	2.93E+06	4.49E+05	8.02E+07
in million Btu/year:	2.41E+03	1.58E+04	6.18E+04	1.07E+05	3.94E+04	3.62E+04	1.00E+04	1.53E+03	2.74E+05
1.4. MILLING MACHINE GROUP									
-per machine, in hp-hr/year:	5.79E+02	3.55E+02	5.76E+02	5.51E+02	5.47E+02	5.75E+02	3.97E+02	3.44E+02	
in kWh-year:	4.32E+02	2.65E+02	4.30E+02	4.11E+02	4.08E+02	4.29E+02	2.96E+02	2.57E+02	
in million Btu/year:	1.47E+00	9.03E-01	1.47E+00	1.40E+00	1.39E+00	1.46E+00	1.01E+00	8.76E-01	
-all machines, in hp-hr/year:	6.84E+05	3.41E+06	2.28E+07	7.06E+07	1.49E+07	2.42E+07	6.08E+06	2.15E+06	1.45E+08
in kWh-year:	5.10E+05	2.54E+06	1.70E+07	5.27E+07	1.11E+07	1.80E+07	4.54E+06	1.60E+06	1.08E+08
in million Btu/year:	1.74E+03	8.68E+03	5.79E+04	1.80E+05	3.79E+04	6.15E+04	1.55E+04	5.47E+03	3.68E+05
1.5. BROACHING MACHINE GROUP									
-per machine, in hp-hr/year:	1.16E+03	5.91E+02	1.17E+03	1.16E+03	1.09E+03	1.17E+03	1.22E+03	1.42E+03	
in kWh-year:	8.62E+02	4.41E+02	8.71E+02	8.64E+02	8.16E+02	8.74E+02	9.13E+02	1.06E+03	
in million Btu/year:	2.94E+00	1.50E+00	2.97E+00	2.95E+00	2.79E+00	2.98E+00	3.11E+00	3.62E+00	
-all machines, in hp-hr/year:	3.81E+04	3.86E+05	3.06E+06	7.91E+06	8.99E+05	6.09E+06	2.85E+05	1.71E+05	1.88E+07
in kWh-year:	2.84E+04	2.88E+05	2.29E+06	5.90E+06	6.70E+05	4.54E+06	2.13E+05	1.27E+05	1.41E+07
in million Btu/year:	9.71E+01	9.81E+02	7.80E+03	2.01E+04	2.29E+03	1.55E+04	7.26E+02	4.34E+02	4.79E+04
1.6. SAWING MACHINE GROUP									
-per machine, in hp-hr/year:	5.00E+02	5.00E+02	5.00E+02	5.00E+02	5.00E+02	5.00E+02	5.00E+02	5.00E+02	
in kWh-year:	3.73E+02	3.73E+02	3.73E+02	3.73E+02	3.73E+02	3.73E+02	3.73E+02	3.73E+02	
in million Btu/year:	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	
-all machines, in hp-hr/year:	1.13E+06	5.23E+06	2.01E+07	2.84E+07	9.46E+06	1.07E+07	4.29E+06	3.50E+06	8.28E+07
in kWh-year:	8.42E+05	3.90E+06	1.50E+07	2.12E+07	7.05E+06	7.97E+06	3.20E+06	2.61E+06	6.17E+07
in million Btu/year:	2.87E+03	1.33E+04	5.10E+04	7.23E+04	2.41E+04	2.72E+04	1.09E+04	8.90E+03	2.11E+05

TABLE 5.1. (contd)

INDUSTRY:	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
2. FRICTIONAL SINK AT TOOL-WORK PIECE INTERFACE									
2.1. ALL MACHINE GROUPS									
hp-hr/year:	5.59E+06	8.31E+07	2.52E+08	5.59E+08	1.41E+08	1.84E+08	6.14E+07	2.04E+07	1.31E+09
in kWh/year:	4.17E+06	6.20E+07	1.88E+08	4.17E+08	1.05E+08	1.38E+08	4.57E+07	1.52E+07	9.74E+08
in billion Btu/year:	1.42E+01	2.11E+02	6.42E+02	1.42E+03	3.59E+02	4.69E+02	1.56E+02	5.18E+01	3.32E+03
2.2. TURNING MACHINE GROUP									
-per machine, in hp-hr/year:	1.89E+03	3.00E+03	1.86E+03	1.88E+03	2.00E+03	1.85E+03	1.74E+03	1.34E+03	
in kWh-year:	1.41E+03	2.24E+03	1.39E+03	1.40E+03	1.49E+03	1.38E+03	1.30E+03	9.97E+02	
in million Btu/year:	4.82E+00	7.63E+00	4.73E+00	4.78E+00	5.10E+00	4.71E+00	4.42E+00	3.40E+00	
-all machines, in hp-hr/year:	1.86E+06	6.28E+07	1.59E+08	3.60E+08	8.66E+07	1.11E+08	4.19E+07	1.18E+07	8.35E+08
in kWh-year:	1.39E+06	4.68E+07	1.18E+08	2.69E+08	6.46E+07	8.27E+07	3.12E+07	8.81E+06	6.23E+08
in million Btu/year:	4.73E+03	1.60E+05	4.04E+05	9.17E+05	2.20E+05	2.82E+05	1.07E+05	3.00E+04	2.12E+06
2.3. DRILLING MACHINE GROUP									
-per machine, in hp-hr/year:	4.85E+02	4.46E+02	4.71E+02	4.46E+02	4.67E+02	4.68E+02	2.42E+02	1.01E+02	
in kWh-year:	3.62E+02	3.33E+02	3.52E+02	3.33E+02	3.48E+02	3.49E+02	1.80E+02	7.51E+01	
in million Btu/year:	1.23E+00	1.13E+00	1.20E+00	1.13E+00	1.19E+00	1.19E+00	6.15E-01	2.56E-01	
-all machines, in hp-hr/year:	1.26E+06	8.26E+06	3.24E+07	5.58E+07	2.06E+07	1.89E+07	5.24E+06	8.02E+05	1.43E+08
in kWh-year:	9.43E+05	6.16E+06	2.41E+07	4.16E+07	1.54E+07	1.41E+07	3.91E+06	5.98E+05	1.07E+08
in million Btu/year:	3.22E+03	2.10E+04	8.24E+04	1.42E+05	5.25E+04	4.82E+04	1.33E+04	2.04E+03	3.65E+05
2.4. MILLING MACHINE GROUP									
-per machine, in hp-hr/year:	7.72E+02	4.73E+02	7.69E+02	7.35E+02	7.30E+02	7.66E+02	5.30E+02	4.59E+02	
in kWh-year:	5.76E+02	3.53E+02	5.73E+02	5.48E+02	5.44E+02	5.71E+02	3.95E+02	3.42E+02	
in million Btu/year:	1.96E+00	1.20E+00	1.96E+00	1.87E+00	1.86E+00	1.95E+00	1.35E+00	1.17E+00	
-all machines, in hp-hr/year:	9.12E+05	4.55E+06	3.03E+07	9.41E+07	1.99E+07	3.22E+07	8.11E+06	2.87E+06	1.93E+08
in kWh-year:	6.80E+05	3.39E+06	2.26E+07	7.02E+07	1.48E+07	2.40E+07	6.05E+06	2.14E+06	1.44E+08
in million Btu/year:	2.32E+03	1.16E+04	7.72E+04	2.40E+05	5.05E+04	8.21E+04	2.06E+04	7.29E+03	4.91E+05
2.5. BROACHING MACHINE GROUP									
-per machine, in hp-hr/year:	1.54E+03	7.89E+02	1.56E+03	1.54E+03	1.46E+03	1.56E+03	1.63E+03	1.90E+03	
in kWh-year:	1.15E+03	5.88E+02	1.16E+03	1.15E+03	1.09E+03	1.17E+03	1.22E+03	1.41E+03	
in million Btu/year:	3.92E+00	2.01E+00	3.96E+00	3.93E+00	3.71E+00	3.98E+00	4.15E+00	4.83E+00	
-all machines, in hp-hr/year:	5.09E+04	5.14E+05	4.09E+06	1.05E+07	1.20E+06	8.12E+06	3.80E+05	2.28E+05	2.51E+07
in kWh-year:	3.79E+04	3.83E+05	3.05E+06	7.86E+06	8.94E+05	6.06E+06	2.84E+05	1.70E+05	1.87E+07
in million Btu/year:	1.29E+02	1.31E+03	1.04E+04	2.68E+04	3.05E+03	2.07E+04	9.67E+02	5.79E+02	6.39E+04
2.6. SAWING MACHINE GROUP									
-per machine, in hp-hr/year:	6.67E+02	6.67E+02	6.67E+02	6.67E+02	6.67E+02	6.67E+02	6.67E+02	6.67E+02	
in kWh-year:	4.97E+02	4.97E+02	4.97E+02	4.97E+02	4.97E+02	4.97E+02	4.97E+02	4.97E+02	
in million Btu/year:	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	
-all machines, in hp-hr/year:	1.51E+06	6.97E+06	2.67E+07	3.79E+07	1.26E+07	1.42E+07	5.72E+06	4.67E+06	1.10E+08
in kWh-year:	1.12E+06	5.20E+06	1.99E+07	2.82E+07	9.40E+06	1.06E+07	4.27E+06	3.48E+06	8.23E+07
in million Btu/year:	3.83E+03	1.77E+04	6.80E+04	9.64E+04	3.21E+04	3.62E+04	1.46E+04	1.19E+04	2.81E+05
3. TOTAL FRICTIONAL SINK									
3.1. ALL MACHINE GROUPS									

TABLE 5.1. (contd)

INDUSTRY:	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
hp-hr/year:	9.79E+06	1.45E+08	4.42E+08	9.78E+08	2.47E+08	3.23E+08	1.07E+08	3.56E+07	2.29E+09
in kWh/year:	7.30E+06	1.08E+08	3.29E+08	7.29E+08	1.84E+08	2.41E+08	8.01E+07	2.66E+07	1.71E+09
in billion Btu/year:	2.49E+01	3.70E+02	1.12E+03	2.49E+03	6.28E+02	8.21E+02	2.73E+02	9.07E+01	5.82E+03
3.2. TURNING MACHINE GROUP									
-per machine, in hp-hr/year:	3.31E+03	5.25E+03	3.26E+03	3.29E+03	3.51E+03	3.24E+03	3.04E+03	2.34E+03	
in kWh-year:	2.47E+03	3.91E+03	2.43E+03	2.45E+03	2.62E+03	2.42E+03	2.27E+03	1.74E+03	
in million Btu/year:	8.43E+00	1.34E+01	8.28E+00	8.36E+00	8.93E+00	8.25E+00	7.73E+00	5.95E+00	
-all machines, in hp-hr/year:	3.25E+06	1.10E+08	2.78E+08	6.31E+08	1.52E+08	1.94E+08	7.33E+07	2.07E+07	1.46E+09
in kWh-year:	2.43E+06	8.20E+07	2.07E+08	4.70E+08	1.13E+08	1.45E+08	5.47E+07	1.54E+07	1.09E+09
in million Btu/year:	8.28E+03	2.80E+05	7.07E+05	1.60E+06	3.86E+05	4.94E+05	1.87E+05	5.26E+04	3.72E+06
3.3. DRILLING MACHINE GROUP									
-per machine, in hp-hr/year:	8.49E+02	7.80E+02	8.25E+02	7.81E+02	8.17E+02	8.19E+02	4.23E+02	1.76E+02	
in kWh-year:	6.33E+02	5.82E+02	6.15E+02	5.82E+02	6.10E+02	6.11E+02	3.15E+02	1.31E+02	
in million Btu/year:	2.16E+00	1.99E+00	2.10E+00	1.99E+00	2.08E+00	2.08E+00	1.08E+00	4.48E-01	
-all machines, in hp-hr/year:	2.21E+06	1.45E+07	5.67E+07	9.77E+07	3.61E+07	3.32E+07	9.17E+06	1.40E+06	2.51E+08
in kWh-year:	1.65E+06	1.08E+07	4.22E+07	7.28E+07	2.69E+07	2.47E+07	6.84E+06	1.05E+06	1.87E+08
in million Btu/year:	5.63E+03	3.68E+04	1.44E+05	2.49E+05	9.19E+04	8.44E+04	2.33E+04	3.57E+03	6.38E+05
3.4. MILLING MACHINE GROUP									
-per machine, in hp-hr/year:	1.35E+03	8.28E+02	1.35E+03	1.29E+03	1.28E+03	1.34E+03	9.27E+02	8.03E+02	
in kWh-year:	1.01E+03	6.18E+02	1.80E+03	9.59E+02	9.52E+02	1.00E+03	6.91E+02	5.99E+02	
in million Btu/year:	3.44E+00	2.11E+00	3.42E+00	3.27E+00	3.25E+00	3.41E+00	2.36E+00	2.04E+00	
-all machines, in hp-hr/year:	1.60E+06	7.96E+06	5.31E+07	1.65E+08	3.47E+07	5.64E+07	1.42E+07	5.02E+06	3.38E+08
in kWh-year:	1.19E+06	5.94E+06	3.96E+07	1.23E+08	2.59E+07	4.21E+07	1.06E+07	3.74E+06	2.52E+08
in million Btu/year:	4.06E+03	2.03E+04	1.35E+05	4.19E+05	8.84E+04	1.44E+05	3.61E+04	1.28E+04	8.59E+05
3.5. BROACHING MACHINE GROUP									
-per machine, in hp-hr/year:	2.70E+03	1.38E+03	2.73E+03	2.70E+03	2.55E+03	2.74E+03	2.86E+03	3.32E+03	
in kWh-year:	2.01E+03	1.03E+03	2.03E+03	2.02E+03	1.91E+03	2.04E+03	2.13E+03	2.47E+03	
in million Btu/year:	6.86E+00	3.51E+00	6.93E+00	6.88E+00	6.50E+00	6.96E+00	7.27E+00	8.44E+00	
-all machines, in hp-hr/year:	8.90E+04	9.00E+05	7.15E+06	1.84E+07	2.10E+06	1.42E+07	6.65E+05	3.98E+05	4.40E+07
in kWh-year:	6.64E+04	6.71E+05	5.33E+06	1.38E+07	1.56E+06	1.06E+07	4.96E+05	2.97E+05	3.28E+07
in million Btu/year:	2.26E+02	2.29E+03	1.82E+04	4.69E+04	5.34E+03	3.62E+04	1.69E+03	1.01E+03	1.12E+05
3.6. SAWING MACHINE GROUP									
-per machine, in hp-hr/year:	1.17E+03	1.17E+03	1.17E+03	1.17E+03	1.17E+03	1.17E+03	1.17E+03	1.17E+03	
in kWh-year:	8.70E+02	8.70E+02	8.70E+02	8.70E+02	8.70E+02	8.70E+02	8.70E+02	8.70E+02	
in million Btu/year:	2.97E+00	2.97E+00	2.97E+00	2.97E+00	2.97E+00	2.97E+00	2.97E+00	2.97E+00	
-all machines, in hp-hr/year:	2.64E+06	1.22E+07	4.68E+07	6.63E+07	2.21E+07	2.49E+07	1.00E+07	8.17E+06	1.93E+08
in kWh-year:	1.97E+06	9.10E+06	3.49E+07	4.94E+07	1.65E+07	1.86E+07	7.47E+06	6.09E+06	1.44E+08
in million Btu/year:	6.71E+03	3.10E+04	1.19E+05	1.69E+05	5.61E+04	6.34E+04	2.55E+04	2.08E+04	4.91E+05
4. FRICTIONAL SINK REDUCTION FROM USING SURFACE MODIFIED TOOLS									
4.1. ALL MACHINE GROUPS									
hp-hr/year:	1.24E+06	1.85E+07	5.61E+07	1.24E+08	3.13E+07	4.10E+07	1.36E+07	4.53E+06	2.90E+08
in kWh/year:	9.27E+05	1.38E+07	4.18E+07	9.26E+07	2.34E+07	3.06E+07	1.02E+07	3.38E+06	2.17E+08
in billion Btu/year:	3.16E+00	4.70E+01	1.43E+02	3.16E+02	7.97E+01	1.04E+02	3.47E+01	1.15E+01	7.39E+02

TABLE 5.1. (contd)

INDUSTRY:	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
4.2. TURNING MACHINE GROUP									
-per machine, in hp-hr/year:	4.21E+02	6.67E+02	4.13E+02	4.17E+02	4.45E+02	4.12E+02	3.86E+02	2.97E+02	
in kWh-year:	3.14E+02	4.97E+02	3.08E+02	3.11E+02	3.32E+02	3.07E+02	2.88E+02	2.21E+02	
in million Btu/year:	1.07E+00	1.70E+00	1.05E+00	1.06E+00	1.13E+00	1.05E+00	9.82E-01	7.56E-01	
-all machines, in hp-hr/year:	4.13E+05	1.40E+07	3.53E+07	8.01E+07	1.93E+07	2.46E+07	9.31E+06	2.62E+06	1.86E+08
in kWh-year:	3.08E+05	1.04E+07	2.63E+07	5.97E+07	1.44E+07	1.84E+07	6.94E+06	1.96E+06	1.38E+08
in million Btu/year:	1.05E+03	3.55E+04	8.98E+04	2.04E+05	4.90E+04	6.27E+04	2.37E+04	6.68E+03	4.72E+05
4.3. DRILLING MACHINE GROUP									
-per machine, in hp-hr/year:	1.08E+02	9.91E+01	1.05E+02	9.91E+01	1.04E+02	1.04E+02	5.37E+01	2.24E+01	
in kWh-year:	8.04E+01	7.39E+01	7.81E+01	7.39E+01	7.74E+01	7.75E+01	4.00E+01	1.67E+01	
in million Btu/year:	2.74E-01	2.52E-01	2.67E-01	2.52E-01	2.64E-01	2.65E-01	1.37E-01	5.69E-02	
-all machines, in hp-hr/year:	2.81E+05	1.84E+06	7.19E+06	1.24E+07	4.59E+06	4.21E+06	1.16E+06	1.78E+05	3.19E+07
in kWh-year:	2.10E+05	1.37E+06	5.36E+06	9.25E+06	3.42E+06	3.14E+06	8.68E+05	1.33E+05	2.38E+07
in million Btu/year:	7.15E+02	4.67E+03	1.83E+04	3.16E+04	1.17E+04	1.07E+04	2.96E+03	4.54E+02	8.10E+04
4.4. MILLING MACHINE GROUP									
-per machine, in hp-hr/year:	1.72E+02	1.05E+02	1.71E+02	1.63E+02	1.62E+02	1.70E+02	1.18E+02	1.02E+02	
in kWh-year:	1.28E+02	7.84E+01	1.27E+02	1.22E+02	1.21E+02	1.27E+02	8.78E+01	7.60E+01	
in million Btu/year:	4.36E-01	2.68E-01	4.35E-01	4.15E-01	4.13E-01	4.33E-01	2.99E-01	2.59E-01	
-all machines, in hp-hr/year:	2.03E+05	1.01E+06	6.74E+06	2.09E+07	4.41E+06	7.17E+06	1.80E+06	6.37E+05	4.29E+07
in kWh-year:	1.51E+05	7.54E+05	5.03E+06	1.56E+07	3.29E+06	5.34E+06	1.34E+06	4.75E+05	3.20E+07
in million Btu/year:	5.15E+02	2.57E+03	1.72E+04	5.32E+04	1.12E+04	1.82E+04	4.59E+03	1.62E+03	1.09E+05
4.5. BROACHING MACHINE GROUP									
-per machine, in hp-hr/year:	3.43E+02	1.75E+02	3.46E+02	3.43E+02	3.24E+02	3.47E+02	3.63E+02	4.21E+02	
in kWh-year:	2.55E+02	1.31E+02	2.58E+02	2.56E+02	2.42E+02	2.59E+02	2.70E+02	3.14E+02	
in million Btu/year:	8.71E-01	4.46E-01	8.80E-01	8.73E-01	8.25E-01	8.84E-01	9.23E-01	1.07E+00	
-all machines, in hp-hr/year:	1.13E+04	1.14E+05	9.08E+05	2.34E+06	2.66E+05	1.81E+06	8.45E+04	5.06E+04	5.58E+06
in kWh-year:	8.43E+03	8.52E+04	6.77E+05	1.75E+06	1.99E+05	1.35E+06	6.30E+04	3.77E+04	4.16E+06
in million Btu/year:	2.88E+01	2.91E+02	2.31E+03	5.96E+03	6.78E+02	4.59E+03	2.15E+02	1.29E+02	1.42E+04
4.6. SAWING MACHINE GROUP									
-per machine, in hp-hr/year:	1.48E+02	1.48E+02	1.48E+02	1.48E+02	1.48E+02	1.48E+02	1.48E+02	1.48E+02	
in kWh-year:	1.10E+02	1.10E+02	1.10E+02	1.10E+02	1.10E+02	1.10E+02	1.10E+02	1.10E+02	
in million Btu/year:	3.77E-01	3.77E-01	3.77E-01	3.77E-01	3.77E-01	3.77E-01	3.77E-01	3.77E-01	
-all machines, in hp-hr/year:	3.35E+05	1.55E+06	5.94E+06	8.42E+06	2.80E+06	3.17E+06	1.27E+06	1.04E+06	2.45E+07
in kWh-year:	2.50E+05	1.16E+06	4.43E+06	6.28E+06	2.09E+06	2.36E+06	9.49E+05	7.73E+05	1.83E+07
in million Btu/year:	8.52E+02	3.94E+03	1.51E+04	2.14E+04	7.13E+03	8.06E+03	3.24E+03	2.64E+03	6.24E+04

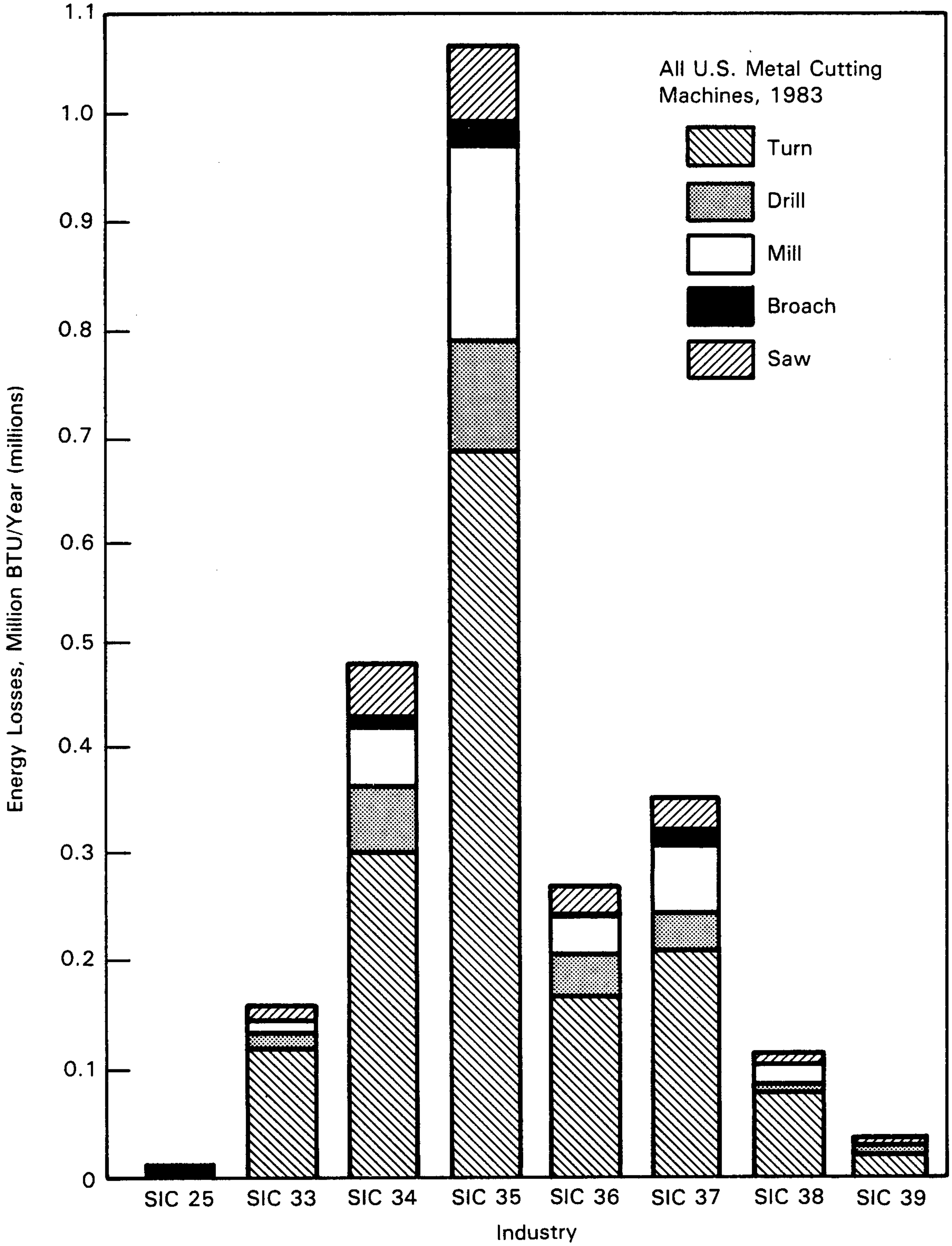

FIGURE 5.1. Frictional Losses at the Drive System

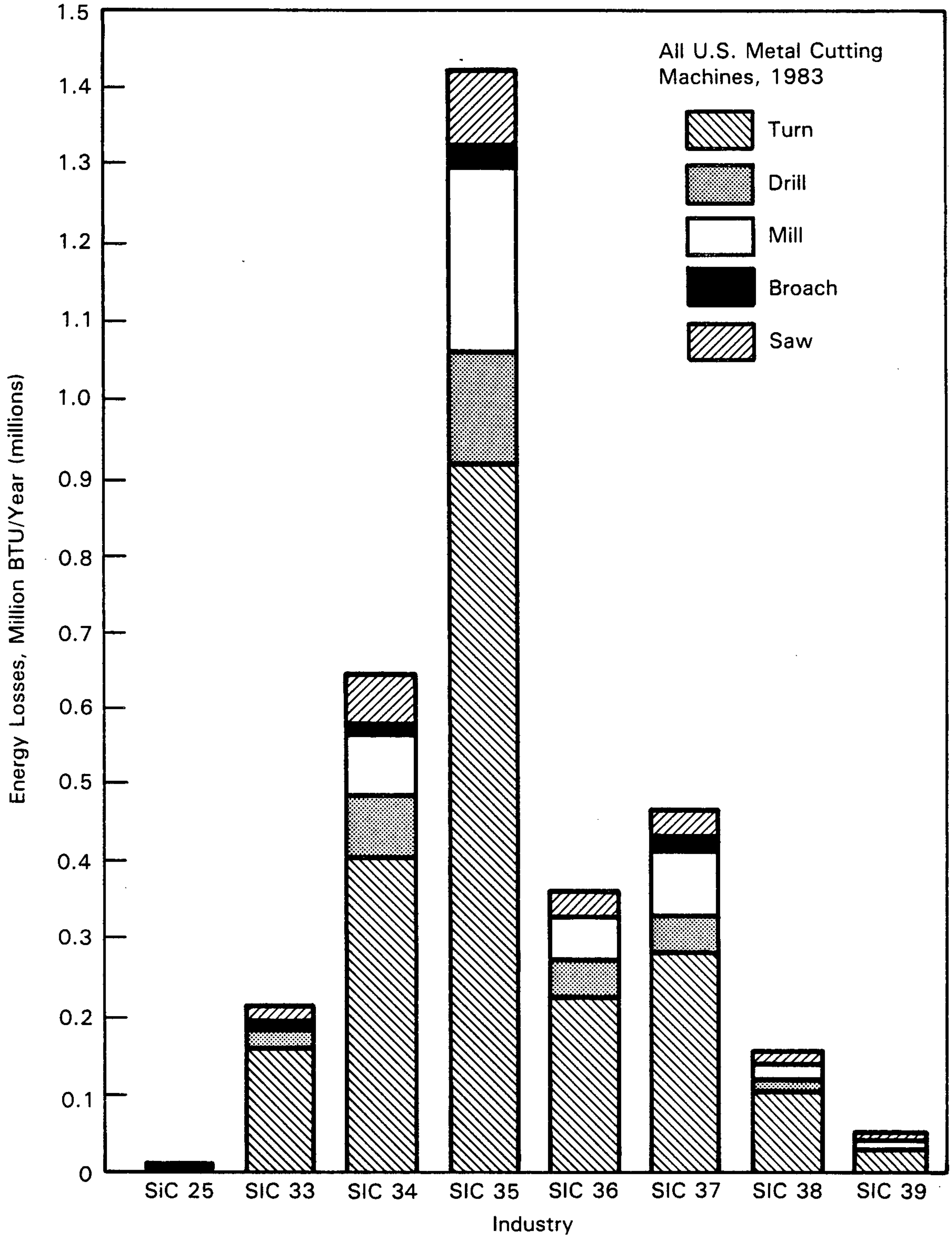

FIGURE 5.2. Frictional Losses at the Tool Point

perspective, Industry Group SIC 35, Machinery Except Electrical, would account for 316 billion Btu/year of the total potential energy savings. Figure 5.3 shows these savings by machine group and industry.

5.1.4 Energy Savings Achievable from Wear Reduction with Surface Modification Technologies

The use of surface modified tools has been shown to increase tool life anywhere from 200 to 1,100 percent. Assuming conservatively that a 600 percent increase in tool life could be achieved, the energy saved annually would be 1,936 billion Btu/year.

5.1.5 Metalcutting Summary

This study estimates that of the 8,133 billion Btu lost per year in the metalcutting tribological sink, approximately 2,675 billion Btu/year, or 33 percent, might be eliminated through the use of surface modified tools.

5.2 EFFECTS OF SURFACE MODIFICATION TECHNOLOGIES IN METALFORMING

Table 5.2 shows calculations for the frictional tribological sink and the energy savings achievable with the use of surface modified tools in metalforming. These calculations were made using an average coefficient of friction of 0.10, a 25 percent decrease in the coefficient of friction when surface modified tools are used, and an efficiency ratio of 0.3 for punching machines. Highlights of the results of these calculations are described below.

5.2.1 The Frictional Sink in Metalforming

As in metalcutting machines, frictional losses in metalforming machines occur at the drive system and the tool point. This study estimates that for a regular work year of 2,000 hours, frictional losses at the drive system of metalforming machines are about 10,400 billion Btu/year; frictional losses at the tool point are 4,000 billion Btu/year. The origins of frictional losses by machine type and industry are shown in Figure 5.4 for losses at the drive system and in Figure 5.5 for losses at the tool point.

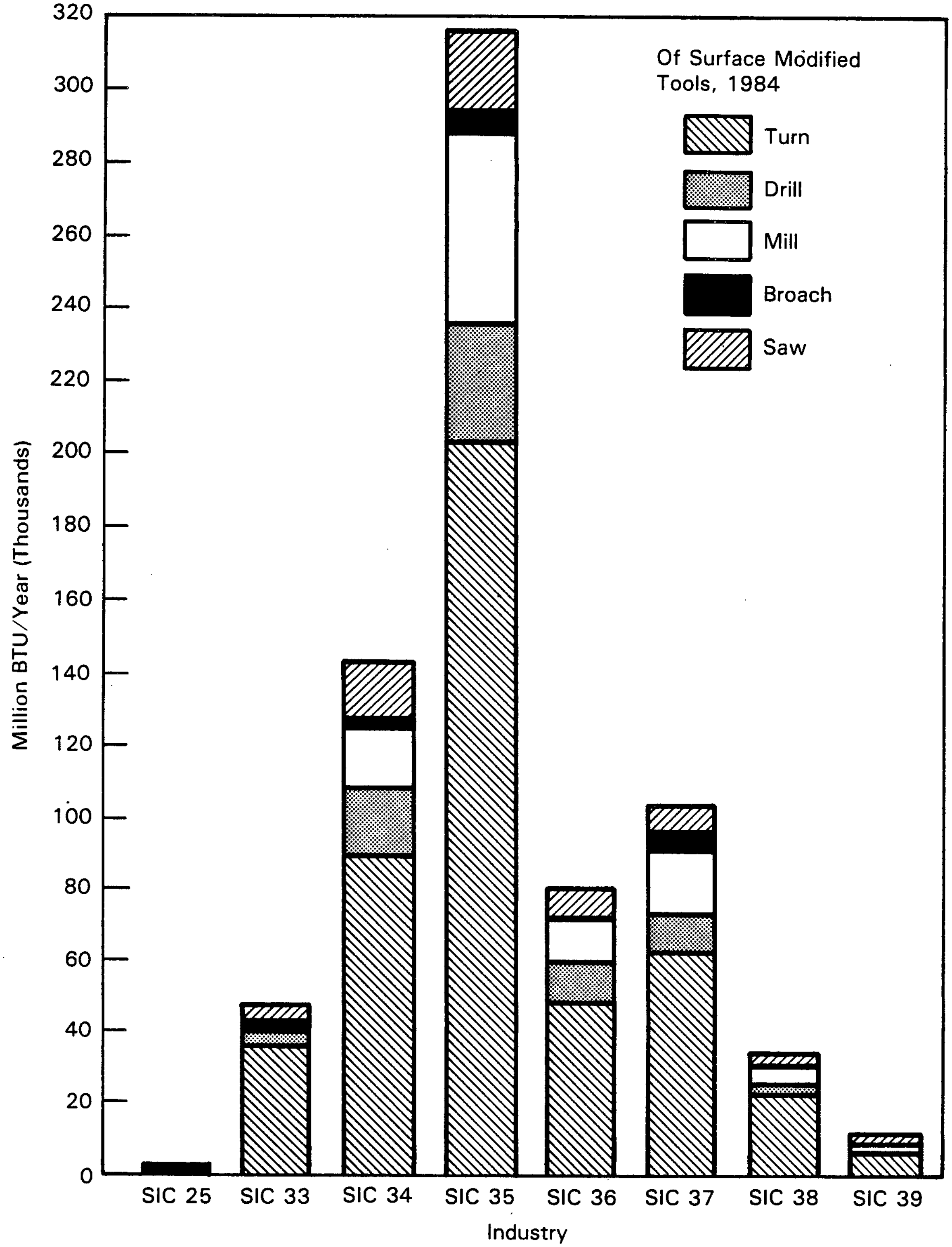

FIGURE 5.3. Metalcutting Energy Savings Potential

TABLE 5.2. Metalforming Energy Savings Estimation Model, Frictional Sink Consumption: up = 0.3; mu = 0.10; u2/u1 = 0.75

INDUSTRY	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
A) MODEL INPUTS									
PUNCHING MACHINES (number of machines):	800	1265	13671	10061	4772	3215	1765	1504	37053
Average motor horsepower (hp):	10	10	10	10	10	10	10	10	
efficiency ratio u:	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	
hours worked per year:	2000	2000	2000	2000	2000	2000	2000	2000	
loss at drive system e (%):	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
PRESSES AND FORGES (number of machines):	9040	16380	114356	46479	45114	32316	11570	14279	289534
Average motor horsepower (hp):	26.35	44.55	34.40	34.21	30.23	36.76	28.91	34.14	
efficiency ratio u:	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	
average coefficient of friction:	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
hours worked per year:	2000	2000	2000	2000	2000	2000	2000	2000	
loss at drive system e (%):	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
EFFECTS OF SURFACE MODIFICATION TECHNOLOGIES:									
ratio of new/old coefficient of friction:	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	
B) RESULTS									
1. FRICTIONAL SINK AT MOTOR DRIVE SYSTEM									
1.1 All machines									
-hp-hr/year:	9.85E+07	2.97E+08	1.63E+09	6.76E+08	5.65E+08	4.88E+08	1.41E+08	2.01E+08	4.09E+09
in kWh-hr/year:	7.34E+07	2.21E+08	1.21E+09	5.04E+08	4.21E+08	3.64E+08	1.05E+08	1.50E+08	3.05E+09
in billion Btu/year:	2.51E+02	7.55E+02	4.14E+03	1.72E+03	1.44E+03	1.24E+03	3.58E+02	5.12E+02	1.04E+04
1.2 Punching machines									
-per machines, in hp-hr/year:	4.00E+03	4.00E+03	4.00E+03	4.00E+03	4.00E+03	4.00E+03	4.00E+03	4.00E+03	
in kWh-hr/year:	2.98E+03	2.98E+03	2.98E+03	2.98E+03	2.98E+03	2.98E+03	2.98E+03	2.98E+03	
in billion Btu/year:	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	
-all machines, in hp-hr/year:	3.20E+06	5.06E+06	5.47E+07	4.02E+07	1.91E+07	1.29E+07	7.06E+06	6.02E+06	1.48E+08
in kWh-hr/year:	2.39E+06	3.77E+06	4.08E+07	3.00E+07	1.42E+07	9.59E+06	5.26E+06	4.49E+06	1.11E+08
in billion Btu/year:	8.14E+00	1.29E+01	1.39E+02	1.02E+02	4.86E+01	3.27E+01	1.80E+01	1.53E+01	3.77E+02
1.3 Presses and forges									
-per machines, in hp-hr/year:	1.05E+04	1.78E+04	1.38E+04	1.37E+04	1.21E+04	1.47E+04	1.16E+04	1.37E+04	
in kWh-hr/year:	7.86E+03	1.33E+04	1.03E+04	1.02E+04	9.02E+03	1.10E+04	8.62E+03	1.02E+04	
in billion Btu/year:	2.68E-02	4.53E-02	3.50E-02	3.48E-02	3.08E-02	3.74E-02	2.94E-02	3.48E-02	
-all machines, in hp-hr/year:	9.53E+07	2.92E+08	1.57E+09	6.36E+08	5.45E+08	4.75E+08	1.34E+08	1.95E+08	3.95E+09
in kWh-hr/year:	7.11E+07	2.18E+08	1.17E+09	4.74E+08	4.07E+08	3.54E+08	9.98E+07	1.45E+08	2.94E+09
in billion Btu/year:	2.42E+02	7.43E+02	4.00E+03	1.62E+03	1.39E+03	1.21E+03	3.40E+02	4.96E+02	1.00E+04
2. FRICTIONAL SINK AT TOOL-WORK PIECE INTERFACE									
2.1 All machines									

TABLE 5.2. (contd)

INDUSTRY	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
hp-hr/year:	3.76E+07	1.11E+08	6.23E+08	2.68E+08	2.16E+08	1.85E+08	5.52E+07	7.65E+07	1.57E+09
in kWh-hr/year:	2.80E+07	8.26E+07	4.64E+08	2.00E+08	1.61E+08	1.38E+08	4.11E+07	5.70E+07	1.17E+09
in billion Btu/year:	9.57E+01	2.82E+02	1.58E+03	6.83E+02	5.50E+02	4.70E+02	1.40E+02	1.95E+02	4.00E+03
2.2 Punching machines									
-per machine, in hp-hr/year:	3.69E+03	3.69E+03	3.69E+03	3.69E+03	3.69E+03	3.69E+03	3.69E+03	3.69E+03	
in kWh-hr/year:	2.75E+03	2.75E+03	2.75E+03	2.75E+03	2.75E+03	2.75E+03	2.75E+03	2.75E+03	
in billion Btu/year:	9.39E-03	9.39E-03	9.39E-03	9.39E-03	9.39E-03	9.39E-03	9.39E-03	9.39E-03	
-all machines, in hp-hr/year:	2.95E+06	4.67E+06	5.05E+07	3.71E+07	1.76E+07	1.19E+07	6.52E+06	5.55E+06	1.37E+08
in kWh-hr/year:	2.20E+06	3.48E+06	3.76E+07	2.77E+07	1.31E+07	8.85E+06	4.86E+06	4.14E+06	1.02E+08
in billion Btu/year:	7.52E+00	1.19E+01	1.28E+02	9.45E+01	4.48E+01	3.02E+01	1.66E+01	1.41E+01	3.48E+02
2.3 Presses and forges									
-per machine, in hp-hr/year:	3.83E+03	6.48E+03	5.00E+03	4.98E+03	4.40E+03	5.35E+03	4.20E+03	4.97E+03	
in kWh-hr/year:	2.86E+03	4.83E+03	3.73E+03	3.71E+03	3.28E+03	3.99E+03	3.14E+03	3.70E+03	
in billion Btu/year:	9.75E-03	1.65E-02	1.27E-02	1.27E-02	1.12E-02	1.36E-02	1.07E-02	1.26E-02	
-all machines, in hp-hr/year:	3.47E+07	1.06E+08	5.72E+08	2.31E+08	1.98E+08	1.73E+08	4.86E+07	7.09E+07	1.43E+09
in kWh-hr/year:	2.58E+07	7.91E+07	4.27E+08	1.72E+08	1.48E+08	1.29E+08	3.63E+07	5.29E+07	1.07E+09
in billion Btu/year:	8.82E+01	2.70E+02	1.46E+03	5.88E+02	5.05E+02	4.40E+02	1.24E+02	1.80E+02	3.65E+03
3. TOTAL FRICTIONAL SINK									
3.1 All machines									
hp-hr/year:	1.36E+08	4.08E+08	2.25E+09	9.45E+08	7.81E+08	6.73E+08	1.96E+08	2.78E+08	5.67E+09
in kWh-hr/year:	1.01E+08	3.04E+08	1.68E+09	7.04E+08	5.82E+08	5.02E+08	1.46E+08	2.07E+08	4.23E+09
in billion Btu/year:	3.46E+02	1.04E+03	5.73E+03	2.40E+03	1.99E+03	1.71E+03	4.99E+02	7.06E+02	1.44E+04
3.2 Punching machines									
-per machine, in hp-hr/year:	7.69E+03	7.69E+03	7.69E+03	7.69E+03	7.69E+03	7.69E+03	7.69E+03	7.69E+03	
in kWh-hr/year:	5.74E+03	5.74E+03	5.74E+03	5.74E+03	5.74E+03	5.74E+03	5.74E+03	5.74E+03	
in billion Btu/year:	1.96E-02	1.96E-02	1.96E-02	1.96E-02	1.96E-02	1.96E-02	1.96E-02	1.96E-02	
-all machines, in hp-hr/year:	6.15E+06	9.73E+06	1.05E+08	7.74E+07	3.67E+07	2.47E+07	1.36E+07	1.16E+07	2.85E+08
in kWh-hr/year:	4.59E+06	7.26E+06	7.84E+07	5.77E+07	2.74E+07	1.84E+07	1.01E+07	8.63E+06	2.13E+08
in billion Btu/year:	1.57E+01	2.48E+01	2.68E+02	1.97E+02	9.34E+01	6.29E+01	3.45E+01	2.94E+01	7.25E+02
3.3 Presses and forges									
-per machine, in hp-hr/year:	1.44E+04	2.43E+04	1.88E+04	1.87E+04	1.65E+04	2.01E+04	1.58E+04	1.86E+04	
in kWh-hr/year:	1.07E+04	1.81E+04	1.40E+04	1.39E+04	1.23E+04	1.50E+04	1.18E+04	1.39E+04	
in billion Btu/year:	3.66E-02	6.18E-02	4.77E-02	4.75E-02	4.20E-02	5.10E-02	4.01E-02	4.74E-02	
-all machines, in hp-hr/year:	1.30E+08	3.98E+08	2.15E+09	8.67E+08	7.44E+08	6.48E+08	1.82E+08	2.66E+08	4.35E+09
in kWh-hr/year:	9.69E+07	2.97E+08	1.60E+09	6.47E+08	5.55E+08	4.83E+08	1.36E+08	1.98E+08	3.24E+09
in billion Btu/year:	3.31E+02	1.01E+03	5.46E+03	2.21E+03	1.89E+03	1.65E+03	4.64E+02	6.77E+02	1.11E+04
4. FRICTIONAL SINK REDUCTION FROM USING SURFACE MODIFIED TOOLS									
4.1 All machines									
hp-hr/year:	1.04E+07	3.09E+07	1.72E+08	7.29E+07	5.97E+07	5.13E+07	1.51E+07	2.12E+07	4.33E+08
in kWh-hr/year:	7.75E+06	2.31E+07	1.28E+08	5.44E+07	4.45E+07	3.82E+07	1.12E+07	1.58E+07	3.23E+08
in billion Btu/year:	2.65E+01	7.87E+01	4.38E+02	1.86E+02	1.52E+02	1.30E+02	3.84E+01	5.39E+01	1.10E+03

TABLE 5.2. (contd)

INDUSTRY	SIC 25	SIC 33	SIC 34	SIC 35	SIC 36	SIC 37	SIC 38	SIC 39	TOTAL
4.2 Punching machines									
-per machine, in hp-hr/year:	7.54E+02	7.54E+02	7.54E+02	7.54E+02	7.54E+02	7.54E+02	7.54E+02	7.54E+02	
in kWh-hr/year:	5.62E+02	5.62E+02	5.62E+02	5.62E+02	5.62E+02	5.62E+02	5.62E+02	5.62E+02	
in billion Btu/year:	1.92E-03	1.92E-03	1.92E-03	1.92E-03	1.92E-03	1.92E-03	1.92E-03	1.92E-03	
-all machines, in hp-hr/year:	6.03E+05	9.53E+05	1.03E+07	7.58E+06	3.60E+06	2.42E+06	1.33E+06	1.13E+06	2.79E+07
in kWh-hr/year:	4.50E+05	7.11E+05	7.68E+06	5.65E+06	2.68E+06	1.81E+06	9.92E+05	8.45E+05	2.08E+07
in billion Btu/year:	1.53E+00	2.43E+00	2.62E+01	1.93E+01	9.15E+00	6.16E+00	3.38E+00	2.88E+00	7.10E+01
4.3 Presses and forges									
-per machine, in hp-hr/year:	1.08E+03	1.83E+03	1.41E+03	1.41E+03	1.24E+03	1.51E+03	1.19E+03	1.40E+03	
in kWh-hr/year:	8.08E+02	1.37E+03	1.05E+03	1.05E+03	9.27E+02	1.13E+03	8.86E+02	1.05E+03	
in billion Btu/year:	2.76E-03	4.66E-03	3.60E-03	3.58E-03	3.16E-03	3.84E-03	3.02E-03	3.57E-03	
-all machines, in hp-hr/year:	9.79E+06	3.00E+07	1.62E+08	6.54E+07	5.61E+07	4.88E+07	1.37E+07	2.00E+07	4.06E+08
in kWh-hr/year:	7.30E+06	2.24E+07	1.21E+08	4.87E+07	4.18E+07	3.64E+07	1.03E+07	1.49E+07	3.02E+08
in billion Btu/year:	2.49E+01	7.63E+01	4.11E+02	1.66E+02	1.43E+02	1.24E+02	3.50E+01	5.10E+01	1.03E+03

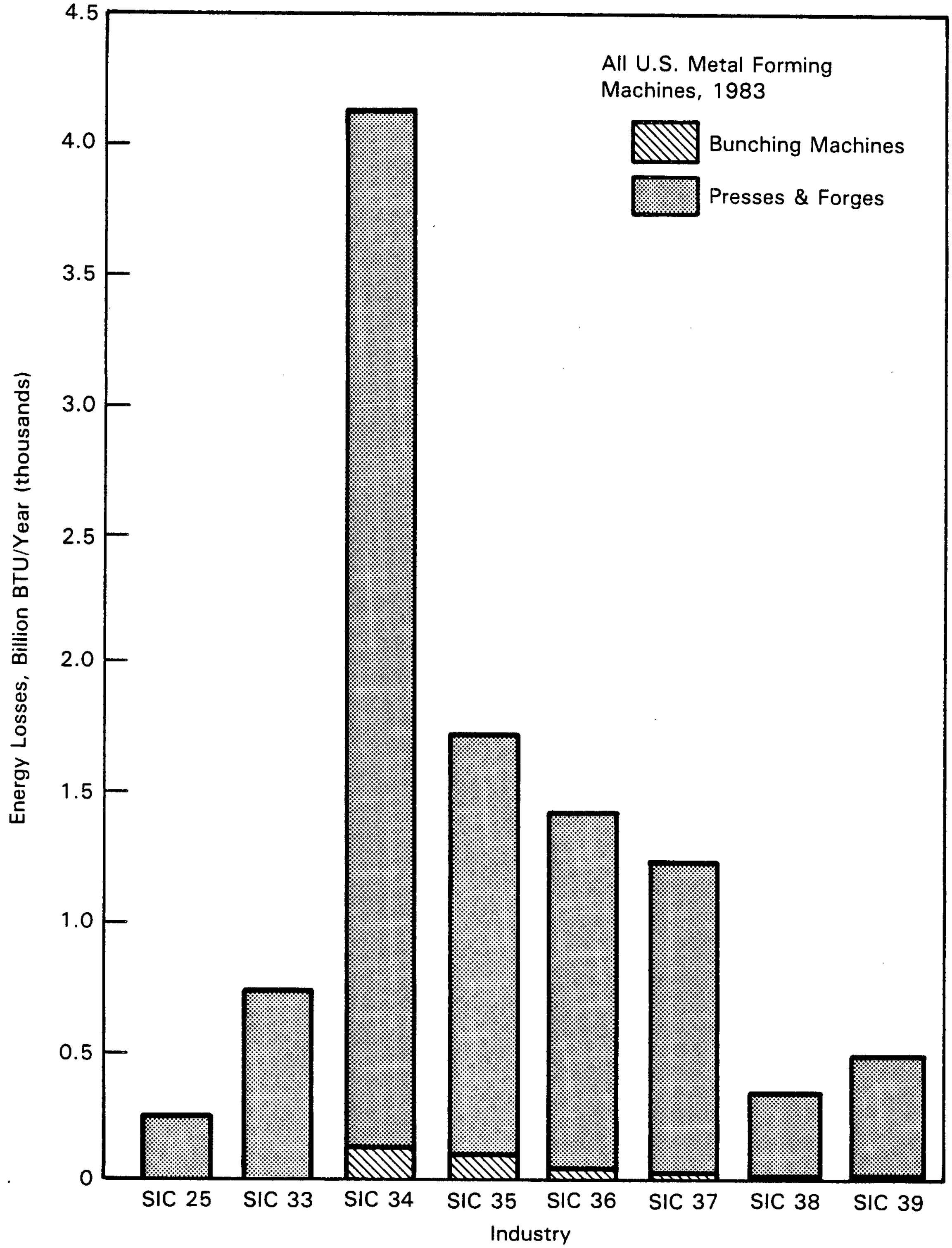

FIGURE 5.4. Frictional Losses at the Drive System

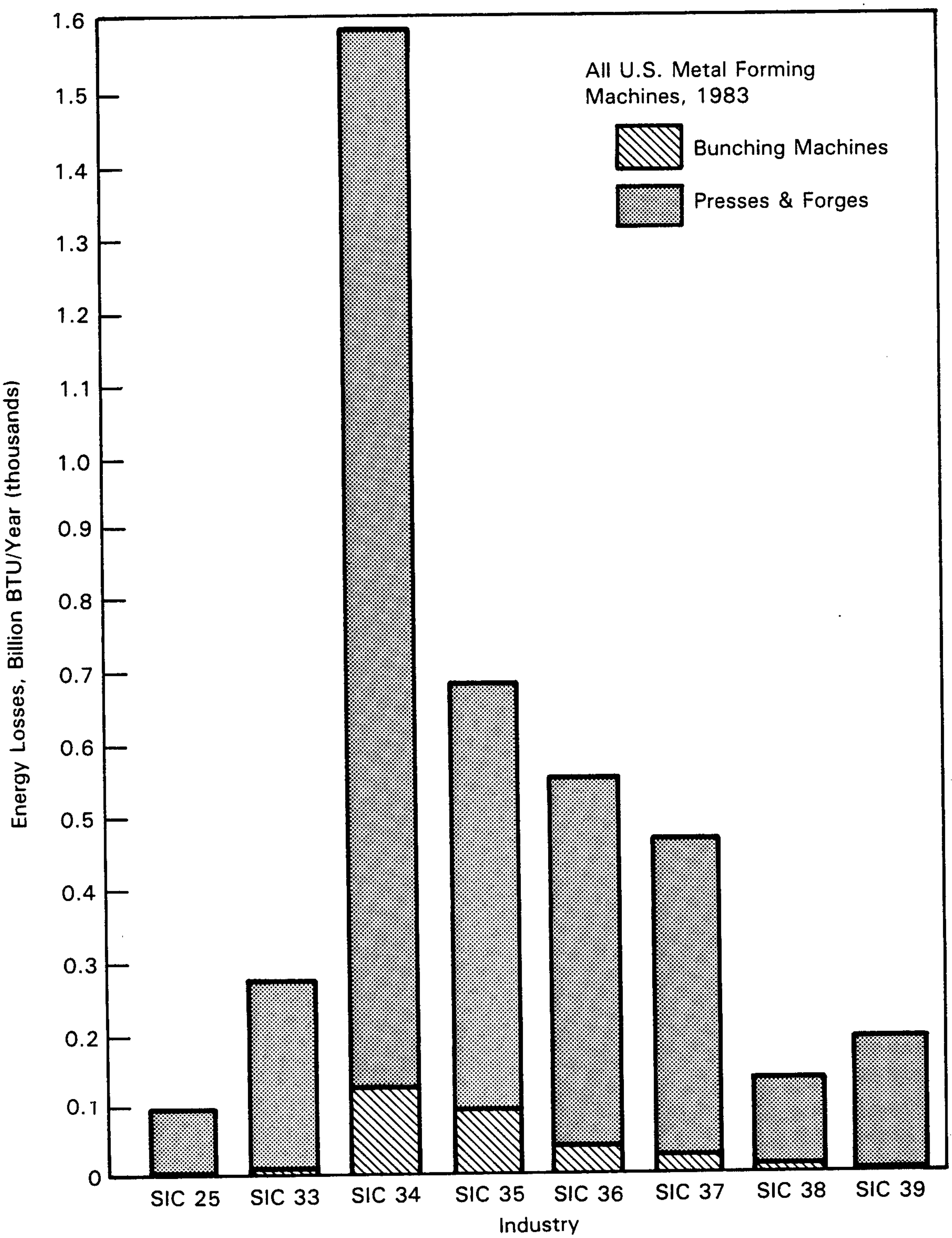

FIGURE 5.5. Frictional Losses at the Tool Point

5.2.2 The Wear Sink in Metalforming

In Section 4.4.4 it was estimated that approximately 272,610 tons of steels were used in 1983 to manufacture metalforming dies, jigs, and fixtures. With 19.2 million Btu/ton as the embodied energy of steels, the wear sink would be 5,370 billion Btu/year.

5.2.3 Energy Savings Achievable from Friction Reduction with Surface Modification Technologies

Assuming that surface modified tools can lower the coefficient of friction by 25 percent, approximately 1,100 billion Btu would be saved from the full-scale use of these tools in metalforming. Figure 5.6 shows these savings by machine group and by industry.

5.2.4 Energy Savings Achievable from Wear Reduction with Surface Modification Technologies

Assuming that a 300 percent increase in tool life is achieved when surface modification is used, the energy savings from wear reduction would be 2,666 billion Btu/year.

5.2.5 Metalforming Summary

Of the 19,770 billion Btu/year lost to friction and wear in metalforming, this study estimates that approximately 4,680 billion Btu/year, or 24 percent, can be saved through the use of surface modified tools.

5.3 DISCUSSION

The estimates for the tribological sink and the energy savings that might be achieved with the use of surface modified tools in metalworking are shown in Table 5.3.

The tribological sink in metalworking is approximately 28 trillion Btu/year, 20 trillion due to friction and 8 trillion to wear. The energy savings achievable with the use of surface modified tools is 7.3 trillion Btu, or 26 percent of the total sink.

Assuming an electricity purchase price of $12/million Btu, the dollar costs of tribological losses total $335 million/year; at the same time, the

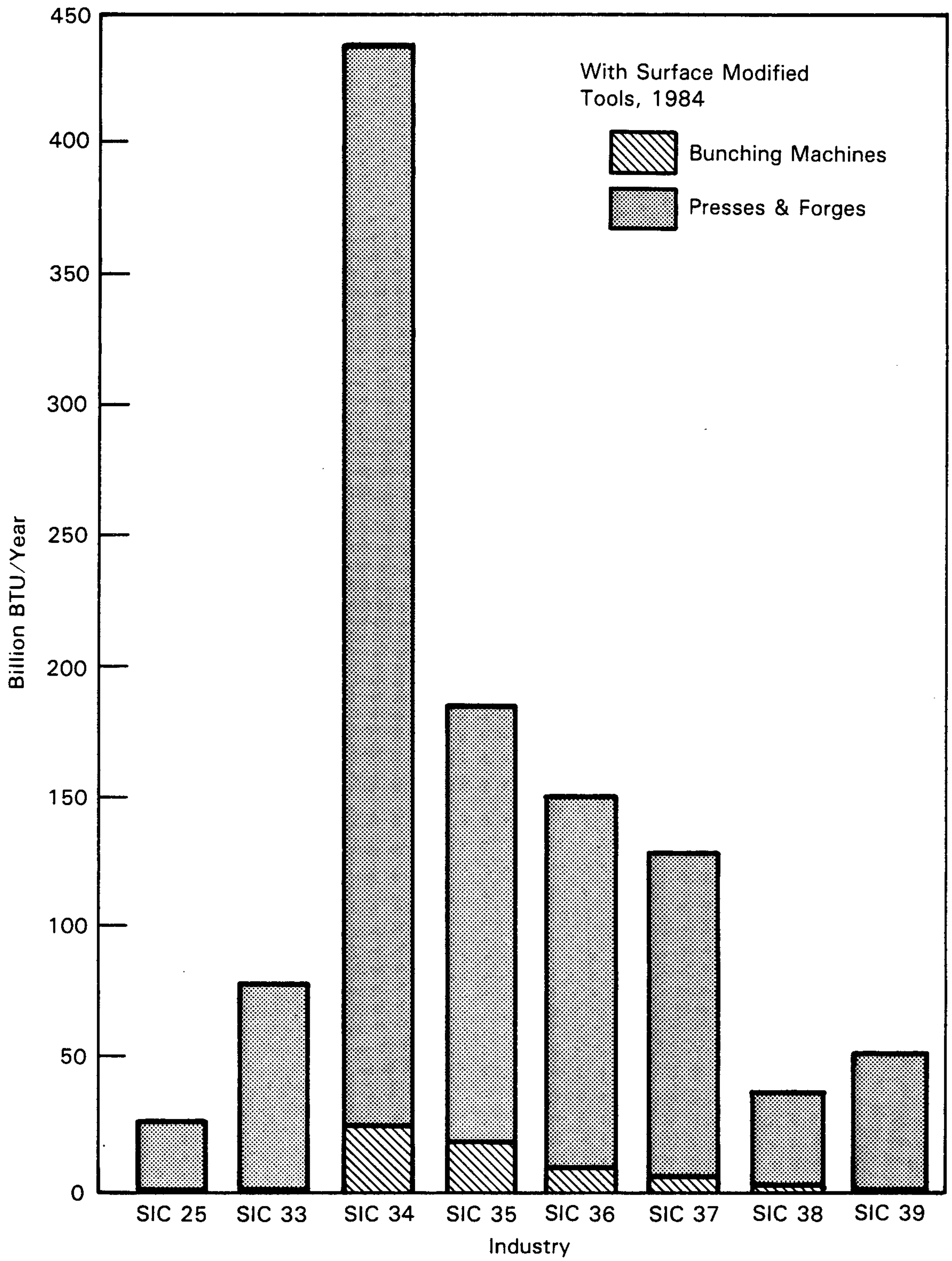

FIGURE 5.6. Metalforming Energy Savings Potential

TABLE 5.3. Tribological Losses and Energy Savings Potential with Surface Modified Tools in Metalworking (billion Btu/year)

Operation		Frictional Sink Drive	Frictional Sink Tool	Wear Sink	Total
Metalcutting:	Losses	2,490	3,320	2,323	8,133
	Savings	0	739	1,936	2,675
Metalforming:	Losses	10,400	4,000	5,370	19,770
	Savings	0	1,100	3,580	4,680

savings with use of surface modified tools would be $88 million/year (see Table 5.4). Note that the dollar losses and savings are averaged over the whole country without regard to regional variations in energy costs.

5.3.1 Upper Bound Estimates

The estimates obtained are probably conservative. Only 72 percent of all metalcutting machines and 74 percent of all metalforming machines are considered in estimating the tribological sinks. Because the basis for eliminating a particular machine type from the study was absence of severe frictional losses at the tool point and amenability of the tools to surface modification, the tool point sink estimates are probably correct and the drive sink estimates are low.

TABLE 5.4. Dollar Values of Tribological Losses and Energy Savings Potential with Surface Modified Tools in Metalworking (million dollars/year)

Operation		Frictional Sink Drive	Frictional Sink Tool	Wear Sink	Total
Metalcutting:	Losses	29.9	39.8	27.8	107.5
	Savings	0	8.9	23.2	32.1
Metalforming:	Losses	124.8	48.0	64.4	237.2
	Savings	0	13.2	43.0	56.2
Cutting and Forming:	Losses	154.7	87.8	92.2	334.7
	Savings	0	22.1	66.2	88.3

The same rationale applies to estimated savings. Because DOE is concerned primarily with surface modification of metalworking tools, this study did not consider the effects of surface modified bearings or drive belts; with surface modification, some energy savings would result. The additional savings would probably be a few tenths of a percent of the frictional losses.

For the wear sink computations, 19.2 million Btu/ton of steel were used, reflecting the assumption that metalworking tools are manufactured from scrap steels in electric furnaces. The embodied energy of steels from ores is equal to approximately 37.4 million Btu/ton. In addition, the wear sink did not include the tools manufactured by large companies that make their own tools.

Assuming then, that the number of machines should be increased by a factor of 1.43 (the study considered only 70 percent of the machines in the United States), that the savings achievable with surface modified machine drive components are approximately 20 percent of the drive sinks, and that the wear sinks should be increased by a factor of 1.95 (the ratio of 37.4 to 19.2), then the sinks and savings in Table 5.3 can be adjusted as shown in Table 5.5. In Table 5.5, the upper bound estimates of the tribological losses and energy savings potential with surface modified tools in metalworking are about twice the more conservative estimates.

TABLE 5.5. Upper Bound Estimates of Tribological Losses and Energy Savings Potential with Surface Modified Tools in Metalworking (billion Btu/year)

Operation		Frictional Sink Drive	Frictional Sink Tool	Wear Sink	Total
Metalcutting:	Losses	3,560	3,320	4,529	11,409
	Savings	712	739	3,775	5,226
Metalforming:	Losses	14,872	4,000	10,472	29,344
	Savings	2,974	1,100	6,910	10,984
Cutting and Forming:	Losses	18,432	7,320	15,001	40,153
	Savings	3,686	1,839	10,658	16,210

5.3.2 Effect of Productivity Increase

An important effect of surface modification technologies is increased productivity of metalworking operations. But the complex tribological implications of increased productivity are difficult to quantify. In both metalcutting and metalforming, surface modified tools increase productivity because of the higher speed and feed rates and the longer productive cutting times. But increased speed and feed rates are likely to increase the tribological sinks in absolute terms: more horsepower is required at the tool point. Increasing the productive cutting time has the same effect. To analyze the productivity aspects of surface modification technologies requires the development of a comparable but different model than the one used in this study.

APPENDIX A

THE METALWORKING-INTENSIVE INDUSTRIES

APPENDIX A

THE METALWORKING-INTENSIVE INDUSTRIES

SIC Code	Industry Group and Industry
25	Furniture and Fixtures
251	Household Furniture
2511	Wood Household Furniture
2512	Upholstered Household Furniture
2514	Metal Household Furniture
2515	Mattresses and Bedsprings
2517	Wood TV and Radio Cabinets
2519	Household Furniture, n.e.c.
252	Office Furniture
2521	Wood Office Furniture
2522	Metal Office Furniture
2531	Public Building and Related Furniture
254	Partitions and Fixtures
2541	Wood Partitions and Fixtures
2542	Metal Partitions and Fixtures
259	Miscellaneous Furniture and Fixtures
2591	Drapery Hardware and Blinds and Shades
2599	Furniture and Fixtures, n.e.c.
33	Primary Metal Industries
331	Blast Furnace and Basic Steel Products
3312	Blast Furnaces and Steel Mills
3313	Electrometallurgical Products
3315	Steel Wire and Related Products
3316	Cold Finishing of Steel Shapes
3317	Steel Pipe and Tubes

SIC Code	Industry Group and Industry
332	Iron and Steel Foundries
3321	Gray Iron Foundries
3322	Malleable Iron Foundries
3324	Steel Investment Foundries
3325	Steel Foundries, n.e.c.
333	Primary Nonferrous Metals
3331	Primary Copper
3332	Primary Lead
3333	Primary Zinc
3334	Primary Aluminum
3339	Primary Nonferrous Metals, n.e.c.
3341	Secondary Nonferrous Metals
335	Nonferrous Rolling and Drawing
3351	Copper Rolling and Drawing
3353	Aluminum Sheet, Plate and Foil
3354	Aluminum Extruded Products
3355	Aluminum Rolling and Drawing, n.e.c.
3356	Nonferrous Rolling and Drawing, n.e.c.
3357	Nonferrous Wire Drawing and Insulating
336	Nonferrous Foundries
3361	Aluminum Foundries
3362	Brass, Bronze and Copper Foundries
3369	Nonferrous Foundries, n.e.c.
339	Miscellaneous Primary Metal Products
3398	Metal Heat Treating
3399	Primary Metal Products, n.e.c.
34	Fabricated Metal Products
341	Metal Cans and Shipping Containers
3411	Metal Cans
3412	Metal Barrels, Drums and Pails
342	Cutlery, Hand Tools and Hardware
3421	Cutlery
3423	Hand and Edge Tools, n.e.c.
3425	Hand Saws and Saw Blades
3429	Hardware, n.e.c.

SIC Code	Industry Group and Industry
343	Plumbing and Heating Except Electric
3431	Metal Sanitary Ware
3432	Plumbing Fittings and Brass Goods
3433	Heating Equipment, Except Electric
344	Fabricated Structural Metal Products
3441	Fabricated Structural Metal
3442	Metal Doors, Sash and Trim
3443	Fabricated Parts Work (Boiler Shops)
3444	Sheet Metal Work
3446	Architectural Metal Work
3448	Prefabricated Metal Buildings
3449	Miscellaneous Metal Work
345	Screw Machine Products, Bolts, etc.
3451	Screw Machine Products
3452	Bolts, Nuts, Rivets and Washers
346	Metal Forgings and Stampings
3462	Iron and Steel Forgings
3463	Nonferrous Forgings
3465	Automotive Stampings
3466	Crowns and Closures
3469	Metal Stampings, n.e.c.
347	Metal Services, n.e.c.
3471	Plating and Polishing
3479	Metal Coating and Allied Services
348	Ordnance and Accessories, n.e.c.
3482	Small Arms Ammunition
3483	Ammunition, Except for Small Arms, n.e.c.
3484	Small Arms
3489	Ordnance and Accessories, n.e.c.
349	Miscellaneous Fabricated Metal Products
3493	Steel Springs, Except Wire
3494	Valves and Pipe Fittings
3495	Wire Springs
3496	Miscellaneous Fabricated Wire Products
3497	Metal Foil and Leaf
3498	Fabricated Pipe and Fittings
3499	Fabricated Metal Products, n.e.c.

SIC Code	Industry Group and Industry
35	Machinery, Except Electrical
351	Engines and Turbines
3511	Turbines and Turbine Generator Sets
3519	Internal Combustion Engines, n.e.c.
352	Farm and Garden Machinery
3523	Farm Machinery and Equipment
3524	Lawn and Garden Equipment
353	Construction and Related Machinery
3531	Construction Machinery
3532	Mining Machinery
3533	Oil Field Machinery
3534	Elevators and Moving Stairways
3535	Conveyors and Conveying Equipment
3536	Hoists, Cranes and Monorails
3537	Industrial Trucks and Tractors
354	Metalworking Machinery
3541	Machine Tools, Metal Cutting Types
3542	Machine Tools, Metal Forming Types
3544	Special Dies, Tools, Jigs and Fixtures
3545	Machine Tool Accessories
3546	Power Driven Hand Tools
3547	Rolling Mill Machinery
3549	Metalworking Machinery, n.e.c.
355	Special Industry Machinery
3551	Food Products Machinery
3552	Textile Machinery
3553	Woodworking Machinery
3554	Paper Industries Machinery
3555	Printing Trades Machinery
3559	Special Industry Machinery, n.e.c.
356	General Industrial Machinery
3561	Pumps and Pumping Equipment
3562	Ball and Roller Bearings
3563	Air and Gas Compressors
3564	Blowers and Fans
3565	Industrial Patterns
3566	Speed Changers, Drives and Gears

SIC Code	Industry Group and Industry
3567	Industrial Furnaces and Ovens
3568	Power Transmission Equipment, n.e.c.
3569	General Industrial Machinery, n.e.c.
357	Office and Computing Machines
3573	Electronic Computing Equipment
3574	Calculating and Accounting Machines
3576	Scales and Balances, Except Laboratory
3579	Office Machines, n.e.c. and Typewriters
358	Refrigeration and Service Machinery
3581	Automatic Merchandising Machines
3582	Commercial Laundry Equipment
3585	Refrigeration and Heating Equipment
3586	Measuring and Dispensing Pumps
3589	Service Industry Machinery, n.e.c.
359	Miscellaneous Machinery, Except Electrical
3592	Carburetors, Pistons, Rings and Valves
3599	Machinery, Except Electrical, n.e.c.
36	Electric and Electronic Equipment
361	Electric Distributing Equipment
3612	Transformers
3613	Switchgear and Switchboard Apparatus
362	Electrical Industrial Apparatus
3621	Motors and Generators
3622	Industrial Controls
3623	Welding Apparatus, Electric
3624	Carbon and Graphite Products
3629	Electrical Industrial Apparatus, n.e.c.
363	Household Appliances
3631	Household Cooking Equipment
3632	Household Refrigerators and Freezers
3633	Household Laundry Equipment
3634	Electric Housewares and Fans
3635	Household Vacuum Cleaners
3636	Sewing Machines
3639	Household Appliances, n.e.c.

SIC Code	Industry Group and Industry
364	Electric Lighting and Wiring Equipment
3641	Electric Lamps
3643	Current-Carrying Wiring Devices
3644	Noncurrent-Carrying Wiring Devices
3645	Residential Lighting Fixtures
3646	Commercial Lighting Fixtures
3647	Vehicular Lighting Equipment
3648	Lighting Equipment, n.e.c.
365	Radio and TV Receiving Equipment
3651	Radio and TV Receiving Sets
3652	Phonograph Records and Prerecorded Tape
366	Communications Equipment
3661	Telephone and Telegraph Apparatus
3662	Radio and TV Communication Equipment
367	Electronic Components and Accessories
3671	Electron Tubes, All Types
3674	Semiconductors and Related Devices
3675	Electronic Capacitors
3676	Electronic Resistors
3677	Electronic Coils and Transformers
3678	Electronic Connectors
3679	Electronic Components, n.e.c.
369	Miscellaneous Electric Equipment and Supplies
3691	Storage Batteries
3692	Primary Batteries, Dry and Wet
3693	X-ray, Electromedical, and Electrotherapeutic Apparatus
3694	Engine Electrical Equipment
3699	Electrical Equipment and Supplies, n.e.c.
37	Transportation Equipment
371	Motor Vehicles and Equipment
3711	Motor Vehicles and Car Bodies
3713	Truck and Bus Bodies
3714	Motor Vehicle Parts and Accessories
3715	Truck Trailers
3716	Motor Homes Produced on Purchased Chassis

SIC Code	Industry Group and Industry
372	Aircraft and Parts
3721	Aircraft
3724	Aircraft Engines and Engine Parts
3728	Aircraft Equipment, n.e.c.
373	Ship and Boat Building and Repairing
3731	Ship Building and Repairing
3732	Boat Building and Repairing
3743	Railroad Equipment
3751	Motorcycles, Bicycles and Parts
376	Guided Missiles, Space Vehicles and Parts
3761	Guided Missiles and Space Vehicles
3764	Space Propulsion Units and Parts
3769	Space Vehicle Equipment, n.e.c.
379	Miscellaneous Transportation Equipment
3792	Travel Trailers and Campers
3795	Tanks and Tank Components
3799	Transportation Equipment, n.e.c.
38	Instruments and Related Products
3811	Engineering and Scientific Instruments
382	Measuring and Controlling Devices
3822	Environmental Controls
3823	Process Control Instruments
3824	Fluid Meters and Counting Devices
3825	Instruments to Measure Electricity
3829	Measuring and Controlling Devices, n.e.c.
3832	Optical Instruments and Lenses
384	Medical Instruments and Supplies
3841	Surgical and Medical Instruments
3842	Surgical Appliances and Supplies
3843	Dental Equipment and Supplies
3851	Ophthalmic Goods

SIC Code	Industry Group and Industry
3861	Photographic Equipment and Supplies
3873	Watches, Clocks and Watchcases
39	Miscellaneous Manufacturing Industries
391	Jewelry, Silverware and Plated Ware
3911	Jewelry, Precious Metal
3914	Silverware and Plated Ware
3915	Jewelers' Materials and Lapidary Work
3931	Musical Instruments
394	Toys and Sporting Goods
3942	Dolls
3944	Games, Toys and Childrens' Vehicles
3949	Sporting and Athletic Goods, n.e.c.
395	Pens, Pencils and Office and Art Supplies
3951	Pens and Mechanical Pencils
3952	Lead Pencils and Art Goods
3953	Marking Devices
3955	Carbon Paper and Inked Ribbons
396	Costume Jewelry and Notions
3961	Costume Jewelry
3962	Artificial Flowers
3963	Buttons
3964	Needles, Pins and Fasteners
399	Miscellaneous Manufactures
3991	Brooms and Brushes
3993	Signs and Advertising Displays
3995	Burial Caskets
3996	Hard Surface Floor Coverings
3999	Manufacturing Industries, n.e.c.

APPENDIX B

<u>SPINDLE DRIVE HORSEPOWER OF SELECTED METALWORKING MACHINES</u>

Appendix B: Spindle Drive Horsepower of Selected Metalworking Machines

MACHINES	DRIVE HP
1. METALCUTTING MACHINES	
1.1 NC TURNING MACHINES	
-Horizontal under 9" chuck	
- Cincinnati Mil. 2-Axis Machine CINTURN Series 1208/1210C	20
- Cincinnati Mil. 2-Axis Machine CINTURN Series 1208/1210U	20
- HITACHI SEIKI NS-A2 Turning Center	15
- Hardinge Brothers Inc. SuperSlant	10
- Fuji Machine Mfg. Co. Model SN	7.5
- Fuji Machine Mfg. Co. Model KN	10
-Horizontal 9" to under 13" chuck	
- Cincinnati Mil. 2-Axis Machine CINTURN Series 1212C	30
- Cincinnati Mil. 2-Axis Machine CINTURN Series 1212U	30
- Cincinnati Mil. CINTURN 2-Axis CNC Chucking Ctr Model 12	50
- Cincinnati Mil. CINTURN 4-Axis CNC Chckng Ctr Model 12CD	50
-Horizontal 13" to under 20" chuck	
- Cincinnati Mil. CINTURN 2-Axis Chucking Ctr Model 18C	0
- Cincinnati Mil. CINTURN 2-Axis Chucking Ctr Model 15C	50
- Cincinnati Mil. CINTURN 2-Axis CNC Trng Ctr Un. Mod. 15U	50
- Cincinnati Mil. CINTURN 2-Axis CNC Trng Ctr Un. Mod. 18U	50
- Cincinnati Mil. CINTURN 4-Axis CNC Chckng Ctr Model 15CD	50
- Cincinnati Mil. CINTURN 4-Axis CNC Chckng Ctr Model 18CD	50
- HITACHI SEIKI NS-S3 Turning Center	20
- Leblond Makino Mach. Tool Co. CNC Turn. Center Baron 25	25
-Horizontal 20" chuck and larger	
- Cincinnati Mil. CINTURN 2-Axis CNC Turning Center M-28ST	50
- Cincinnati Mil. CINTURN 2-Axis CNC Ctr Chckng Mod. 28STC	50
- Cincinnati Mil. CINTURN 2-Axis CNC Ctr Chckng Mod. 36STC	60
- Cincinnati Mil. CINTURN 2-Axis CNC Trng Ctr Un. Mod. 21U	60
- Cincinnati Mil. CINTURN 2-Axis CNC Trng Ctr Un. Mod. 24U	60
- Cincinnati Mil. CINTURN 2-Axis CNC Trng Ctr Un. Mod. 28U	60
- Leblond Makino Mach. Tool Co. CNC Turn. Center Baron 40	40
- Leblond Makino Mach. Tool Co. CNC Turn. Center Baron 60	60
- RD&D Corp. Machine Tool Div. High HP Roll Turning Lathe	400
-Vertical turn & bore (VTM, VBM)	
- MFL Machine Tool Inc.	75
- S & S Machinery Co. Supermill CNC 40	55
- S & S Machinery Co. Supermill CNC 60	80
- S & S Machinery Co. Supermill CNC 72	80
- S & S Machinery Co. Supermill CNC 80	80
- S & S Machinery Co. Supermill CNC 100	100

Appendix B: (contd)

MACHINES	DRIVE HP
- S & S Machinery Co. Supermill CNC 120	100
- S & S Machinery Co. Supermill CNC 140	100
- S & S Machinery Co. Supermill CNC 200	125
- S & S Machinery Co. Supermill CNC 240	150
- S & S Machinery Co. Supermill CNC 300	175
1.2 NON NC TURNING MACHINES	
-Eng & tlrm (not tracer) over 8" to 16" swing	
- SIGMA Machinery Inc. Model SN40-16"	7.5
- Nardini International Inc. Model TT-1000S/E 10"	1.5
- Nardini International Inc. Model TT-1200S/E 12"	1.5
- S & S Machinery Co. Lansing Gap Bed Lathe Model 15P 15"	5
- S & S Machinery Co. Lansing Gap Bed Lathe Model 16T 16"	10
- S & S Machinery Co. Lansing Gap Bed Lathe Model 18T 16"	10
- Intermark Hartford Corp. Precision Lathe Model 1430 14"	5
- Polamco Model TUM35 14"	4
-Eng & tlrm (not tracer) over 16" swing	
- SIGMA Machinery Inc. Mdel SN63-25"	10
- SIGMA Machinery Inc. SIGMA-VOLMAN Eng. Lathe Type SU100	35
- S & S Machinery Co. Lansing Gap Bed Lathe Model 18G 18"	15
- Polamco Tarnow TUJ 50M 22"	13.6
- Polamco Model TUG40 17"	7.5
- Polamco Model TUG45 19"	10
- Polamco Model TUJ50 21"	10
- Polamco Model TUR50 H.D. 20"	15
- Polamco Model TUR63A 25"	18
- Polamco Model TPL90 36"	30
-Tracer lathes (all sizes)	
- S & S Machinery Co. Lansing G Facing Tracing Lathe 52"	10
- S & S Machinery Co. Lansing G Facing Tracing Lathe 60"	10
- S & S Machinery Co. Lansing G Facing Tracing Lathe 82"	20
- S & S Machinery Co. Lansing G Facing Tracing Lathe 120"	30
-Turret lathes (all non-NC)	
- SIGMA Machinery Inc. SIGMA-TOS Ram Type #4 model SR50	11
-Vertical turning and boring mills (VTM,VBM)	
- SIGMA Mach. Inc. SIGMA-TOS VBTM Type SKQ12	54
1.3 NC BORING MACHINES	
-Horiz. boring, drilling & milling (bar machining)	

Appendix B: (contd)

MACHINES	DRIVE HP
- DECKEL FP4NC Universal Milling & Boring Machine	5.5
- DECKEL FP5NC Universal Milling & Boring Machine	8
- Wotan Machine Tools Model B 75/105 MNC	12.5
- Wotan Machine Tools Model B 75/150 SNC	28
- Wotan Machine Tools Model B 105 MNC	20
- Wotan Machine Tools Model B 120 MNC	20
- Wotan Machine Tools Model Rapid IR/6	50
- Wotan Machine Tools Model B 75 Tel. 1	12.5
- Wotan Machine Tools Model B 75/105 Tel. 1	12.5
- Wotan Machine Tools Model B 75/120 Tel. 1	20
1.4 NON NC BORING MACHINES	
-Hor. bore, drill, mill (bar mach) table & planer type	
- SIGMA Mach. Inc. SIGMA-TOS Type WH63, 2-1/2" bar	8
- SIGMA Mach. Inc. SIGMA-TOS Type W9A, 3-1/2" bar	10
-Hor. bore, drill, mill (bar mach) floor type	
- SIGMA Mach. Inc. SIGMA-TOS Type WHN 13	50
- SIGMA Mach. Inc. SIGMA/SKODA Heavy duty HBM	70
-Precison, horizontal and vertical	
- SIGMA Mach. Inc. SIGMA-TOS VTM type SJK 10B (50" swing)	87
- SIGMA Mach. Inc. SIGMA-TOS VTM Type SKJ 20 (90" swing)	120
1.5 NON NC DRILLING MACHINES	
-Vertical upright, hand or power feed	
- Jacobson Tool & Mfg Co. Model 75H Drill-O-Matic	10
-Radial	
- SIGMA Mach. Inc. SIGMA-MAS Type VO50	6
- SIGMA Mach. Inc. SIGMA-MAS Type VRM50A	15
- DoAll Model D-50100R	5
1.6 NC MACHINING CENTERS	
-Automatic tool change: vertical Y-axis 26" or less	
- Cincinnati Mil. CINTIMATIC 5VC Model 750 (Y=20")	5
- Cincinnati Mil. CINTIMATIC 20VC Model 2000 (Y=25")	20
- Hurco Mfg. Co. Hurco MD3 (Y= 20")	8
- Hurco Mfg. Co. Hurco MD1 (Y= 16")	5
- MOOG Inc Model 83-3000MC (Y=10")	5
-Automatic tool change: vertical Y-axis over 26"	

Appendix B: (contd)

MACHINES	DRIVE HP
- Schmiede Machine & Tool Corp. UB-710 VMC (Y=40")	7.5
- Brown & Sharpe Mfg. Co. System 1500VC (Y=40")	10
- Briggs-Weaver/Kuraki Model KV-1600 (Y=27.6")	25
- Giddings & Lewis Model 15VFC (Y=36")	15
-Automatic tool change: horizontal Y-axis under 27"	
- Leblond Makino Mach. Tool Co. Model MC 65 (Y=20")	10
- Leblond Makino Mach. Tool Co. Model MC 40 (Y=15 3/4")	10
- Kearney & Trecker Milwaukee-Matic 180 (Y=20")	10
- Hitachi Seiki U.S.A. Inc. HA-400 SEIKIMATIC (Y= 20")	7.5
- Ex-Cell-O Workcenter 208 Machine (Y=24")	25
- Deckel Corp. Model DZ4 (Y=16")	10
-Automatic tool change: horizontal Y-axis 27" or over	
- Ex-Cell-O Workcenter Machine Model 508 (Y=48")	25
- Ikegai American Corporation BX110P (Y=39")	10
- Toyoda Machinery USA Inc Model FHN100T (Y=47")	30
- Cincinnati Mil. CIM-XCHANGER 40HC (Y=40")	40
- Leblond Makino Mach. Tool Co. Model MC 100 (Y=39 3/8"	20
- Leblond Makino Mach. Tool Co. Model MC 1210 (Y=39.5")	30
- Leblond Makino Mach. Tool Co. Model MC 1213 (Y=51.5")	30
- Leblond Makino Mach. Tool Co. Model MC 1510 (Y=39.5")	30
- Leblond Makino Mach. Tool Co. Model MC 1513 (Y=51.5")	30
1.7 NC MILLING MACHINES	
-Profiling and duplicating	
- Leblond Makino Mach. Tool Co. Model FD106 (Vertical)	15
- Leblond Makino Mach. Tool Co. Model FD128 (Vertical)	25
- Leblond Makino Mach. Tool Co. Model FD178 (Vertical)	25
- Leblond Makino Mach. Tool Co. Model FD220 (Vertical)	25
- Leblond Makino Mach. Tool Co. Model H1210 (Horizontal)	30
- Leblond Makino Mach. Tool Co. Model H1710 (Horizontal)	30
- Leblond Makino Mach. Tool Co. Model H2210 (Horizontal)	30
- Leblond Makino Mach. Tool Co. Model H2213 (Horizontal)	30
- Leblond Makino Mach. Tool Co. Model H2513 (Horizontal)	30
1.8 NON NC MILLING MACHINES	
-General purpose, knee or bed: vertical	
- SIGMA Mach. Inc. SIGMA-TOS Type FA3AV	7.5
- SIGMA Mach. Inc. SIGMA-TOS Type FA4AV	10
- Hurco Manufacturing Company Inc. Model SM1	3
- Hurco Manufacturing Company Inc. Model SM2	3
-General purpose, knee or bed: horizontal	

MACHINES	DRIVE HP
- SIGMA Mach. Inc. SIGMA-TOS Type FA3AH	7.5
- SIGMA Mach. Inc. SIGMA-TOS Type FA4AH	10
- Rigid Machine Tool Inc. NF100 Two Spindle Milling Mach.	7.5
- DoAll Model FVH-205	8
-Automatic and manufacturing	
- SIGMA Mach. Inc. Type FD40V	22.5
-Profiling and dupplicating	
- Droop & Rein Model FS 1255kc	20
-Die sinking, engraving, pantograph	
- Cincinnati Milacron 28" Vertical HYDRO-TEL	15
1.9 GEAR CUTTING AND FINISHING MACHINES	
-Gear hobbers	
- SIGMA Mach. Inc. SIGMA-VOLMAN 71" Univ. GHM, Type OF16	37
- SIGMA Mach. Inc. SIGMA-VOLMAN 28" Univ. GHM, Type OF71	24
- SIGMA Mach. Inc. SIGMA-VOLMAN 43" Univ. GHM, Type OF10	24
-Gear shapers	
- SIGMA Mach. Inc. SIGMA-TOS Type OH020	3.5
- SIGMA Mach. Inc. SIGMA-TOS Type OH050	5.5
- S & S Machinery Co. Lansing Gear Shaping Machine Mod. 6	3
- S & S Machinery Co. Lansing Gear Shaping Machine Mod. 4	12
- S & S Machinery Co. Lansing Gear Shaping Machine Mod. 3	7
-Gear tooth finish (grinding,lap, shave etc.)	
- Hey Machine Tools Inc. Hey No. 10	1.5
1.10 NC GRINDING MACHINES (ALL TYPES)	
- Bryant Grinder Corp. Lectraline LL1	0.75
- Bryant Grinder Corp. Lectraline LL2	1.5
- Bryant Grinder Corp. Lectraline LL3	3
- Bryant Grinder Corp. Lectraline LL3-55	3
- Bryant Grinder Corp. Lectraline LL4	10
- Cincinnati Milacron Centerless Grnd. Mach. Mod. AE 220-8	20
- Cincinnati Milacron Centerless Grdg Mach. Mod. AE 220-12	20
- Cincinnati Milacron Centerless Grdg Mach. Mod. AE 330-15	30
- Cincinnati Milacron Centerless Grdg Mach. Mod. AE 350-20	50
1.11 NON NC GRINDING MACHINES	
-External: plain center type	

Appendix B: (contd)

MACHINES	DRIVE HP
- SIGMA Mach. Inc. SIGMA-TOS Super Prec. Univ. Type BUA16A	4
- Cincinnati Milacron Plain Grinding Machine 14"	25
- Cincinnati Milacron Plain Series 370	20
- Cincinnati Milacron Plain Series 380	25
-External: universal center type	
- SIGMA Mach. Inc. SIGMA-TOS Hydr. Universal Type BU 28	13
- Polamco / Jote. Schaudt Univ. Cylindrical Mod. A-440N	7.5
-External: centerless (including shoe type)	
- Cincinnati Milacron Model CINCO 15	15
- Cincinnati Milacron CENTURAMIC 200 Series	20
- ESTARTA Y ECENARRO Model ESTARTA 327	10
- ESTARTA Y ECENARRO Model ESTARTA EE 301	10
- ESTARTA Y ECENARRO Model ESTARTA EE 312	15
- ESTARTA Y ECENARRO Model ESTARTA EE 320	20
- ESTARTA Y ECENARRO Model ESTARTA EE 322	30
- ESTARTA Y ECENARRO Model ESTARTA EE 325	30
- ESTARTA Y ECENARRO Model ESTARTA EE 327	50
- ESTARTA Y ECENARRO Model ESTARTA EE 330	50
-External: chucking	
- Cincinnati Milacron Chicking Grinding Machine No. 1	5
- Cincinnati Milacron Chicking Grinding Machine No. 2	15
-Surface: rotary table, horizontal and vertical	
- Cincinnati Milacron Model 161	1
- S & S Machinery Co. Elgin Model RTC 500	5
-Surface: reciprocating, vertical and horizontal, power	
- SIGMA Mach. Inc. Auto. Hydr. Surf. Grinder Type BPH320A	10
- SIGMA Mach. Inc. Auto. Hydr. Surf. Grinder Type BRH 20A	8.5
- SIGMA Mach. Inc. Auto. Hydr. Surf. Grinder Type BRH 40A	19
- DoAll Model D824-12	5
- Polamco Model FNC-25	3
-Tool and cutter	
- SIGMA Mach.Inc. Type BN102A/AS	1.2
- SIGMA Mach.Inc. Type BN102B	1.2
- Cincinati Milacron Model No. 2MT	1
- Intermark Hartford Corp	1
- Polamco Model NUA-25M	1.5
-Bench, floor and snag	

Appendix B: (contd)

MACHINES	DRIVE HP
- Queen City Mach. Tool Co. Model WU FU Q-2B	1
- Queen City Mach. Tool Co. Model WUFUR-1B	0.75
- Queen City Mach. Tool Co. Model WUFAV-1P	0.33
- Queen City Mach. Tool Co. Model WUMOK30-11-F	5
-Disk grinders, single and double spindle	
- Queen City Mach. Tool Co. Disc Grinder 10"	3
- Queen City Mach. Tool Co. Disc Grinder 20"	10
- Queen City Mach. Tool Co. Disc Grinder 30"	20
-Abrasive belts (except finishing)	
- Waldemar Machine Tools 8" Vertical Sander/Grinder	5
- HILL ACME CO. Abrasive Belt Grinder	100
1.12 HONING, LAPPING, POLISHING MACHINES	
-Polishing stands (incl. abrasive belts-not grinding)	
- Queen City Machine Tool Company Mod. 75B (Polish & Buff)	5
- Queen City Machine Tool Company Mod. 50B (Polish & Buff)	7.5
- Queen City Machine Tool Co. Model 100B (Polish & Buff)	10
- Queen City Machine Tool Co. Model 12B2 (Bearing buffer)	1
- Queen City Machine Tool Co. Model 13B2 (Bearing buffer)	2
- Queen City Machine Tool Co. Model 14B2 (Bearing buffer)	3
- Queen City Machine Tool Co. Model 15B2 (Bearing buffer)	5
1.13 THREADING MACHINES	
- Teledyne Landis Machine Model 10/16B	4
1.14 CUTOFF AND SAWING MACHINES	
-Hacksaws	
- DoAll Model C-3232M Cut-Off Power Saw	25
- DoAll Model AC-2016 Aluminum Cut-Off Saw	25
-Abrasive wheels	
- W. J. Savage Co. Inc. Sever-All Model 1-B	3
- W. J. Savage Co. Inc. Savage/Campbell Model 2	10
- W. J. Savage Co. Inc. Savage/Campbell Model 102A	10
- W. J. Savage Co. Inc. Savage/Campbell Model 223	10
- W. J. Savage Co. Inc. Savage/Campbell Model 265	10
- W. J. Savage Co. Inc. Savage/Campbell Model 270	10
- W. J. Savage Co. Inc. Savage/Campbell Model 302	10
- W. J. Savage Co. Inc. Savage/Campbell Model 476	15
- W. J. Savage Co. Inc. Savage/Campbell Model 342	25
- W. J. Savage Co. Inc. Savage/Campbell Model 364	40

Appendix B: (contd)

MACHINES	DRIVE HP
- W. J. Savage Co. Inc. Savage/Campbell Model 406	15
- W. J. Savage Co. Inc. Savage/Campbell Model 481	40
- W. J. Savage Co. Inc. Savage/Campbell Model 612	75
- W. J. Savage Co. Inc. Sever-All Model 1-B4	5
- W. J. Savage Co. Inc. Sever-All Model 52-A	10
- W. J. Savage Co. Inc. Sever-All Model 22-A	10
- W. J. Savage Co. Inc. Abrasive Plate Saw Model WJS-10	15
- W. J. Savage Co. Inc. Abrasive Plate Saw Model WJS-20	30
- W. J. Savage Co. Inc. Abrasive Plate Saw Model WJS-30	60
- W. J. Savage Co. Inc. Abrasive Plate Saw Model WJS-40	150
-Band saws, countour sawing and filing	
- DoAll Model C-1220A	10
- DoAll Model C-1216A Power Saw	5
- DoAll Model C-916	2
- DoAll Model 2612-D15	5
- DoAll Model 3613-1	3
- DoAll Model 2613-3	7.5
- HEM Inc. HE&M Saw Model 500	1
- HEM Inc. HE&M Saw Model 750	2
- HEM Inc. HE&M Saw Model 1000A	3
- HEM Inc. HE&M Saw Model 1000AH	3
- HEM Inc. HE&M Saw Model 1200A	5
- HEM Inc. HE&M Saw Model 1200LA	5
- HEM Inc. HE&M Saw Model 1250RB	5
- HEM Inc. HE&M Saw Model 1500A	10
2. METALFORMING MACHINES	
2.1 NC PUNCHING AND SHEARING MACHINES	
-NC shearing machines	
- Muller-Wiengarten AG Segment Notching Mach. Type NNS1-16	7.5
2.2 NON NC PUNCHING & SHEARING MACHINES	
-Punching machines (incl. comb. punching & shearing)	
- Japan Automatic Machine Co. Model BPN100S 1T	0.5
- Japan Automatic Machine Co. Model BPN300S 3T	0.5
- Japan Automatic Machine Co. Model BPN505L 5T	1
- Bihler Press, Universal Automatic Punching Model RM40	4
- Bihler Press, Universal Automatic Punching, Model [illegible]	7.5
- Bihler Press, Universal Automatic Punching Model GRM100	15
-Plate and sheet shears: mechanical	
- Boschert GmbH Model PN4 Notcher & shearer	4.8

MACHINES	DRIVE HP
-Plate and sheet shears: hydraulic	
- Rousselle Presses Inc. Model S125-4	3
- Rousselle Presses Inc. Model S250-4	4
- Rousselle Presses Inc. Model S250-8	10
- Rousselle Presses Inc. Model S250-10	10
- Rousselle Presses Inc. Model S250-12	10
- Rousselle Presses Inc. Model S500-8	25
- Rousselle Presses Inc. Model S500-10	25
- Rousselle Presses Inc. Model S500-12	25
- Boschert GmbH Model LB15 Notcher & shearer	6.6
2.3 NON NC BENDING AND FORMING MACHINES (POWER)	
-Press brakes: mechanical	
- Rousselle Presses Inc. Heavy Duty OBS Line Model G50 50T	3
- Rousselle Presses Inc. Heavy Duty OBS Line Model G65 65T	5.5
- Rousselle Presses Inc. Heavy Duty OBS Model G110 110T	7.5
- Rousselle Presses Inc. Heavy Duty OBS Model G135 135T	15
- Rousselle Presses Inc. Heavy Duty OBS Model G175 175T	20
-Press brakes: hydraulic and pneumatic	
- Rousselle Presses Inc. Model H25-4 25T	3
- Rousselle Presses Inc. Model H40-4 40T	4
- Rousselle Presses Inc. Model H90-12 90T	10
- Rousselle Presses Inc. Model H35-12 135T	10
- Comeq Inc / Geka Microcrop-36 Hydraulic Ironworker	3
-Bending rolls, sheet and plate	
- The Lockformer Co. Lockformer Model L-9	2
- The Lockformer Co. Lockformer Model L-7	2
- The Lockformer Co. Lockformer Model L-10DS	5
- The Lockformer Co. Lockformer Model L-14DS	5
- The Lockformer Co. Lockformer Model L-16DS	10
- Waldemar Machine Tools, Plate Bending Roll Model 16-6	7.5
- Waldemar Machine Tools, Plate Bending Roll Model 10-8	7.5
- Waldemar Machine Tools, Plate Bending Roll Model 20-6	10
- Waldemar Machine Tools, Plate Bending Roll Model 16-8	10
- Waldemar Machine Tools, Plate Bending Roll Model 14-10	10
- Waldemar Machine Tools, Plate Bending Roll Model 32-6	15
- Waldemar Machine Tools, Plate Bending Roll Model 24-8	15
- Waldemar Machine Tools, Plate Bending Roll Model 20-10	15
- Waldemar Machine Tools, Plate Bending Roll Model 48-6	25
- Waldemar Machine Tools, Plate Bending Roll Model 48-8	25
- Waldemar Machine Tools, Plate Bending Roll Model 36-10	25
-Bending rolls, angles, bars,shapes pipes	
- Comeq, Inc / Roundo Model R2	3.5

MACHINES	DRIVE HP
- Comeq, Inc / Roundo Model R3	4.6
- Comeq, Inc / Roundo Model R3S	6.3
- Comeq, Inc / Roundo Model R4	8.6
- Comeq, Inc / Roundo Model R4S	10
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- Comeq, Inc / Roundo Model R5S	17.5
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- Comeq, Inc / Roundo Model R8S	60
- Comeq, Inc / Roundo Model R9S	75
- Comeq, Inc / Roundo Model R10S	100
-Rotary bending and forming machines	
- Teledyne Pines Model 3/4	0.75
- Teledyne Pines Model 1	1
- Teledyne Pines Model 1 1/4	1.25
-Ram and press bending machines	
- Teledyne Pines Model 3-T	20
- Teledyne Pines Model 5-T	20
- Teledyne Pines Model 6-T	20
- Teledyne Pines Model 14-T	20
- Teledyne Pines Model 25-T	25
- Teledyne Pines Model 30-T	20
- Teledyne Pines Model 40-T	20
2.4 MECHANICAL PRESSES-POWER (NOT FORGES)	
-Open back (OBI) & gap: 51 tons and over	
- Rousselle Presses Model G2-150 150T	15
- Rousselle Presses Model G2-200 200T	20
- Rousselle Presses Model G2-250 250T	25
- Rousselle Presses Model G2-300 300T	30
-Vertical straight side or arch: single point	
- Oak Products Inc. High Speed Press 30T	10
- Oak Products Inc. High Speed Press 60T	15
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPSR 63T	5.5
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPSR 75T	7.5
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPRR 100T	10
- Oak Products Inc. High Speed Press 100T	25
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPRR 130T	15
- Oak Products Inc. High Speed Press 150T	30
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPRR 160T	20
- Oak Products Inc. High Speed Press 200T	40
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPRR 200T	20
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DEPRR 250T	25

MACHINES	DRIVE HP
- Oak Products Inc. High Speed Press 300T	50
-Two point: 300 tons or under	
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DARR 63/630 63	10
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Model DARR 75/630 75	15
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Mod DARR 110/830 110	20
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Mod DARR 160/830 160	25
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Mod DARR 200/1020 20	30
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Mod DARR 250/1020 25	40
- Rousselle Presses Model S2-150	15
- Rousselle Presses Model S2-200 200T	20
- Rousselle Presses Model S2-250 250T	25
-Two point: 301 tons or over	
- Ferro Tool Inc/ Gebr. Edelhoff GmbH Mod DARR 320/1020 32	40
- Rousselle Presses Model S2-300 300T	30
2.5 HYDRAULIC PRESSES (NOT FORGES)	
-Vertical, straight side, or column	
- Dake Corporation Die Try-out press Model 18-350 25T	10
- Dake Corporation Die Try-out press Model 18-359 25T	10
- Dake Corporation Die Cast Trimming press Mod. 27-320 25T	15
- Dake Corporation Model 27-410 25T	15
- Lauffer Presses Inc. Fast Acting press Type RPT 25 25T	7.4
- Dake Corporation Die Try-out press Model 18-351 50T	10
- Dake Corporation Model 27-411 50T	15
- Lauffer Presses Inc. Fast Acting press Type RPT 63 61T	15
- Dake Corporation Model 27-412 75T	15
- Lauffer Presses Inc. Fast Acting press Type RPT 160 176T	30
- Dake Corporation Model 27-413 100T	20
- Dake Corporation Model 27-414 150T	25
- Dake Corporation Die Cast Trimming press M. 27-324 150T	20
- Dake Corporation Model 27-415 200T	40
- Dake Corporation Die Cast Trimming press M. 27-325 200T	30
- Dake Corporation Model 27-416 300T	40
- Dake Corporation Die Cast Trimming press M. 27-326 300T	40
- Dake Corporation Model 27-417 400T	75
- Dake Corporation Model 27-418 500T	75
- Dake Corporation Model 27-419 600T	75
-C-Frame or gap: 15 tons or under	
- Dake Corporation Norta-Matic Press 4T	3
- Dake Corporation Norta-Matic Press 6T	7.5
- Dake Corporation Norta-Matic Press 12T	10
- Greenerd Press & Machine Co. Model HA-4-5 4T	10
- Greenerd Press & Machine Co. Model HA-4-8L2 4T	5
- Greenerd Press & Machine Co. Model HA-8-8 8T	15

Appendix B: (contd)

MACHINES	DRIVE HP
- Greenerd Press & Machine Co. Model HA-8-8L2 8T	5
- Greenerd Press & Machine Co. Model HA-12-11 12T	20
- Greenerd Press & Machine Co. Model HA-12-11L2 12T	5
- Eitel Presses Straightening Presses Model RP10 11T	3
-C-frame or gap: over 15 tons	
- Dake Corporation Norta-Matic Press 25T	15
- Dake Corporation Norta-Matic Press 50T	30
- Dake Corporation Norta-Matic Press 75T	40
- Dake Corporation Norta-Matic Press 100T	50
- Dake Corporation Open Gap C-Frame Model 28-402 25T	10
- Dake Corporation Open Gap C-Frame Model 28-404 50T	20
- Dake Corporation Open Gap C-Frame Model 28-405 75T	20
- Dake Corporation Open Gap C-Frame Model 28-406 100T	25
- Eitel Presses Straightening Presses Model RP16 17.5T	3
- Eitel Presses Straightening Presses Model RP25 27.5T	4
- Eitel Presses Straightening Presses Model RP40 44T	5.5
- Eitel Presses Straightening Presses Model RP60 66T	10
- Eitel Presses Straightening Presses Model RP100 110T	10
- Eitel Presses Straightening Presses Model RP160 175T	20
- Eitel Presses Straightening Presses Model RP250 275T	20
-Vertical, double action	
- Dake Corporation Movable Frame Press Model 19-435 25T	2
- Dake Corporation Movable Frame Press Model 19-436 50T	2
- Dake Corporation Movable Frame Press Model 19-437 75T	2
- Dake Corporation Movable Frame Press Model 19-438 150T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-380 25T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-381 50T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-382 50T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-383 125T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-384 150T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-385 200T	7.5
- Dake Corporation H Frame Heavy Duty, Mod. 23-386 250T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-387 300T	10
- Dake Corporation H Frame Heavy Duty, Mod. 23-388 400T	20
- Dake Corporation H Frame Heavy Duty, Mod. 23-389 500T	25
- Dake Corporation H Frame Heavy Duty, Mod. 23-390 600T	30
2.6 COIL PROCESSING SYSTEMS	
- Ruesch Machine Co. Model No. 149 Slitter	25
- Ruesch Machine Co. Model No. 129 Rolling Mill	40
2.7 THREAD ROLLING MACHINES	
- Teledyne Landis Machine Model 10TRM	3
- Teledyne Landis Machine Model Lanhyrol	10
- Teledyne Landis Machine Model 32TFRI	20

APPENDIX C

SPINDLE DRIVE HORSEPOWER OF SELECTED MACHINE TOOLS

Appendix C: Spindle Drive Horsepower of Selected Machine Tools

MACHINE TYPE	DRIVE HORSEPOWER L (hp)	H (hp)	A (hp)
1. METALCUTTING MACHINES			
1.1 NC TURNING MACHINES			
-Horizontal under 9" chuck	7.5	20	13.75
-Horizontal 9" to under 13" chuck	30	50	40
-Horizontal 13" to under 20" chuck	20	50	35
-Horizontal 20" chuck and larger	40	60	50
-Vertical turn & bore (VTM, VBM)	75	150	112.5
1.2 NON NC TURNING MACHINES			
-Eng & tlrm (not tracer) over 8" to 16" swing	4	7.5	5.75
-Eng & tlrm (not tracer) over 16" swing	10	30	20
-Tracer lathes (all sizes)	10	20	15
1.3 NC BORING MACHINES			
-Hozizontal bore, drill, mill (bar machining)	8	28	18
1.4 NON NC BORING MACHINES			
-Hor. bore, drill, mill (bar mach) table & planer type	8	10	9
-Hor. bore, drill, mill (bar mach) floor type	50	70	60
-Precison, horizontal and vertical	87	120	103.5
1.6 NON NC DRILLING MACHINES			
-Radial	5	16	10.5
1.7 NC MACHINING CENTERS			
-Automatic tool change: vertical Y-axis 26" or less	8	20	14
-Automatic tool change: vertical Y-axis over 26"	7.5	25	16.25
-Automatic tool change: horizontal Y-axis under 27"	7.5	25	16.25
-Automatic tool change: horizontal Y-axis 27" or over	20	30	25
1.8 NC MILLING CENTERS			
-Profiling and dupplicating	15	25	20
1.9 NON NC MILLIMG MACHINES			
-General purpose, knee or bed: vertical	3	10	6.5
-General purpose, knee or bed: horizontal	7.5	10	8.75
-Automatic and manufacturing		22.5	11.25

MACHINE TYPE	DRIVE HORSEPOWER L (hp)	H (hp)	A (hp)
1.10 GEAR CUTTING AND FINISHING MACHINES			
-Gear hobbers	24	37	30.5
-Gear shapers	3	12	7.5
1.11 NC GRINDING MACHINES (ALL TYPES)	1.5	30	15.75
1.12 NON NC GRINDING MACHINES			
-External: plain center type	20	25	22.5
-External: universal center type	7.5	13	10.25
-External: centerless (including shoe type)	15	50	32.5
-External: chucking	5	15	10
-Surface: reciprocating, vertical and horizontal, power	5	19	12
-Tool and cutter	1	1.5	1.25
-Bench, floor and snag	0.33	5	2.665
-Disk grinders, single and double spindle	3	20	11.5
-Abrasive belts (except finishing)	5	100	52.5
1.13 HONING, LAPPING, POLISHING MACHINES			
-Polishing stands (incl. abrasive belts-not grinding)	1	10	5.5
1.17 CUTOFF AND SAWING MACHINES			
-Abrasive wheels	10	60	35
-Band saws, countour sawing and filing	1	10	5.5
2. METALFORMING MACHINES			
2.2 NC PUNCHING & SHEARING MACHINES			
-Punching machines (incl. comb. punching & shearing)	0.5	15	7.75
-Plate and sheet shears: hydraulic	3	25	14
2.4 NON NC BENDING AND FORMING MACHINES (POWER)			
-Press brakes: mechanical	3	20	11.5
-Press brakes: hydraulic and pneumatic	3	10	6.5
-Bending rolls, sheet and plate	2	25	13.5
-Bending rolls, angles, bars, shapes, pipes	3.5	100	51.75
-Rotary bending and forming machines	0.75	1.25	1
-Ram and press bending machines	20	25	22.5
2.5 MECHANICAL PRESSES-POWER (NOT FORGES)			
-Open back (OBI) &gap: 51 tons and over	15	30	22.5
-Vertical straight side or arch:single point	5.5	50	27.75
-Two point: 300 tons or under	10	40	25
-Two point: 301 tons or over	30	40	35

Appendix C: (contd)

MACHINE TYPE	DRIVE HORSEPOWER L (hp)	H (hp)	A (hp)
2.6 HYDRAULIC PRESSES (NOT FORGES)			
-Vertical, straight side or column	7.5	75	41.25
-C-Frame or gap:15 tons or under	3	20	11.5
-C-frame or gap: over 15 tons	4	40	22
-Vertical, double action	10	20	15
2.8 COIL PROCESSING SYSTEMS	25	40	32.5
2.12 THREAD ROLLING MACHINES	3	20	11.5

Note: HP=spindle horsepower, hp. L=low, H=high, A=average

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